VOLUME XLIII NUMBER 7

THE
JOURNAL OF GEOLOGY

October-November 1935

SOME INTRUSIONS AND THEIR WALL ROCKS IN THE SIERRA NEVADA

EVANS B. MAYO
Cornell University

ABSTRACT

Along the eastern slope of the southern Sierra Nevada, California, an irregular, discontinuous septum of metamorphic rocks separates two great composite intrusions. The nature and structural relations of the metamorphic and plutonic rocks along a portion of the septum between Mono Lake and Owens Valley are sketched. The field evidence indicates that stoping and assimilation have played a minor rôle; and that the intrusions were forcefully emplaced. It also suggests that the intrusions are distinctly later than the folding.

INTRODUCTION

For six field seasons the writer has been studying the geology of an area along the eastern slope of the Sierra Nevada between Mono Lake and Owens Valley, California. During this time much attention has been given to the pre-Cretaceous metamorphic rocks and the late Jurassic[1] intrusions that have invaded them. The objective has been to determine the mode of emplacement of the intrusions.

[1] N. E. A. Hinds, "The Jurassic Age of the Last Granitoid Intrusives in the Klamath Mountains and Sierra Nevada, California," *Amer. Jour. Sci.*, Vol. XXVII (1934), pp. 182–92.

Since it may be several years before the detailed results of the investigation are ready to publish, it is hoped that this preliminary paper will be of interest. It sketches briefly the nature and general tectonic relations of these crystalline rocks, and presents some conclusions which seem warranted by the data now at hand. The field work has yielded little information concerning the genesis of the magma and the cause of its ascent; therefore these fundamental problems cannot be considered here. No discussion is attempted of geologic features younger than the intrusions.

Location.—The approximate location is given in Figure 1, which fits on the southeastern corner of Ernst Cloos's recently published map[2] and extends about 30 miles beyond the limit of his work. It does not quite bridge the gap between the map of Cloos and that of Knopf.[3]

PHYSICAL CONDITIONS

The eastern front of the Sierra Nevada is a maturely dissected scarp, 3,800 to 11,000 feet high,[4] formed by faulting. In this area, the greatest relief along the scarp is somewhat more than 6,000 feet, and the highest points along the crest are over 13,000 feet above sea level. This mountain wall faces, and is indented by, a broad, roughly elliptical, sunken basin in which are located the headwaters of Owens River. Beyond the northern margin of the map, Mono Lake, the saline remnant of a more extensive Pleistocene body of water, lies in a similar sunken basin. Southward, also beyond the limits of the map, the Sierra faces the Inyo Mountains across the deep elongated graben known as Owens Valley.

Because of rugged topography and Pleistocene glaciation,[5] the pre-Cretaceous formations are well exposed along the escarpment, but their continuation in the downthrown block is mainly covered

[2] Ernst Cloos, "Der Sierra Nevada Pluton," *Geol. Rundschau*, Vol. XXII (1931), Heft 6, pp. 372–84; "The Structure of the Sierra Nevada Batholith," *XVI Intl. Geol. Cong. Guidebook 16* (1933), Excursion C-1, p. 42.

[3] Adolph Knopf, "A Geologic Reconnaissance of the Inyo Range and Eastern Slope of the Southern Sierra Nevada, California," *U.S. Geol. Surv. Prof. Paper 110* (1918).

[4] F. E. Matthes, "Geography and Geology of the Sierra Nevada," *XVI Intl. Geol. Cong. Guidebook 16* (1933), Excursion C-1, p. 26.

[5] Eliot Blackwelder, "Pleistocene Glaciation in the Sierra Nevada and Basin Ranges," *Geol. Soc. Amer. Bull. 42* (1931), pp. 865–922.

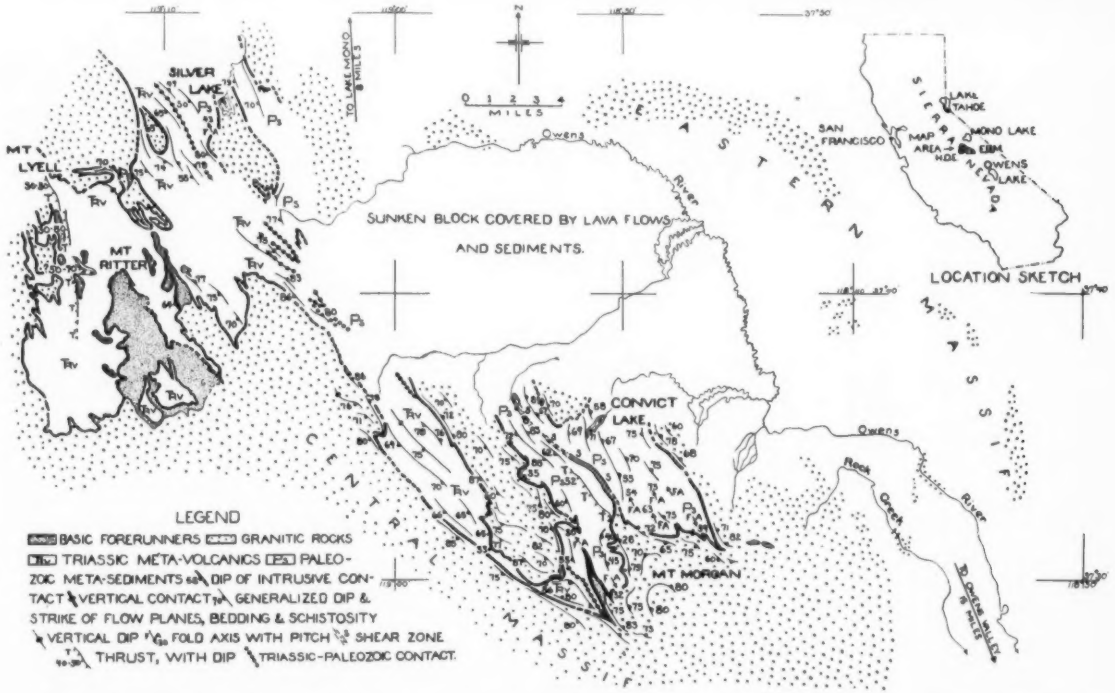


FIG. 1.—Generalized tectonic map of the pre-Cretaceous formations near the headwaters of Owens River, in eastern California. The portion mapped by H. D. Erwin is indicated in the location sketch.

by younger deposits. Locally, Tertiary lavas, not yet stripped from the crest of the range, conceal the underlying structure, and in the northern part of the area a mantle of late Pleistocene or Recent volcanic ash covers some of the gentler slopes. Northeast of Owens River, minor fault blocks project above the younger deposits and furnish isolated outcrops of the crystalline foundation.

PRE-CRETACEOUS ROCKS

MAJOR STRUCTURAL UNITS

The igneous intrusions and their metamorphosed wall rocks, where exposed, are indicated on the map. Among these formations the following major structural units may be distinguished:

1. *Central massif.*—On the southwest there appears the margin of an extensive granitic area marked "central massif." The lobate projection immediately east of Mount Lyell is part of the same unit. These two masses are portions of the irregular eastern border of the vast, granitoid core of the Sierra Nevada. The investigations of Hans Cloos, Robert Balk,[6] and Ernst Cloos[7] have done much to reveal the inner structure of this huge composite batholith.

2. *Eastern massif.*—In the eastern part of the area is what appears to be another vast expanse of granitic rocks (marked "eastern massif"), exposed locally along the steep front of the Sierra and in isolated scarps beyond. Outcrops also occur in the gorges of Owens River and Rock Creek where these streams have eroded the younger formations. This granitic mass is the eastern batholith, recently noted by Ernst Cloos.[8]

3. *Septum.*—Separating these two intrusive groups is a broad, very irregular, partition of intensely deformed metamorphic rocks, referred to as a "septum." In this area the septum is pierced by a number of minor intrusions.

The metamorphics seem to end toward the southeast in two sharp termini. A mile or two beyond the southern margin of the map,

[6] Hans Cloos, "Bau und Bewegung der Gebirge in Nordamerika, Skandinavien, und Mitteleuropa," *Fortschr. d. Geol. u. Pal.*, Vol. VII, Heft 21 (1928), pp. 245–64.

[7] *Op. cit.*

[8] Ernst Cloos, "Sierra Nevada Batholiths and the Mother Lode," *Geol. Soc. Amer. Bull. 44* (1933), abst., pp. 79–80.

however, the septum reappears, and Mr. Chasey[9] found it to continue for many miles as a sinuous band, locally only a few hundred feet in width, separating the eastern batholith from the central massif. Apparently, the septum follows the crest of the Sierra and extends, with irregularities and interruptions, from the vicinity of Mono Lake nearly to Owens Lake, a distance of almost a hundred miles. As shown on the reconnaissance map by Knopf,[10] the southern part of the septum is badly disrupted.

4. *Roof remnant.*—Erwin, who has mapped the metamorphic area around Mount Ritter,[11] regards that unit as a remnant of the batholith roof. Since this roof remnant is attached to the eastern wall of the central massif, he calls it an "attached roof pendant." This remnant receives several intrusive lobes from the central massif, and is pierced by a number of basic forerunners.

METAMORPHIC ROCKS

The rocks of the septum and of the roof remnant around Mount Ritter are intensely folded and, with local exceptions, the folds trend N35-45°W. Steep dips (60° to 90°) prevail, but much gentler ones are occasionally found, as indicated in Figure 2.

These metamorphic rocks include two distinct series:

1. *Paleozoic meta-sediments.*—An irregular band, consisting of strongly deformed marine sediments, now metamorphosed to phyllitic and slaty mylonites, associated with marble and quartzite, occupies the eastern part of the septum. In general, the thermal metamorphism of these rocks has been of low grade, and the original bedding is usually preserved, except in some of the slates and in certain dense, recrystallized mylonites. The dip and strike of the bedding in the meta-sediments are shown in Figure 1.

Cleavage, essentially parallel to the axial planes of the folds, is usually more or less distinct. It is best in the phyllites and slates, poorly developed in the marbles, and absent in some quartzites and recrystallized mylonites. As a rule (but not always) there is a dis-

[9] K. L. Chasey, personal communication.

[10] Adolph Knopf, *op. cit.*

[11] H. D. Erwin, "Geology and Mineral Resources of Northeastern Madera County, California," *Calif. Jour. Mines and Geol.*, Vol. XXX (1934), p. 19.

tinct tendency for the cleavage to become more pronounced near igneous contacts. It is sometimes possible, especially near intrusive margins, to detect a linear elongation, or stretching. In the slates and phyllites small light-colored bodies, possibly fossils, are stretched into spindles. In the marbles, fragments of crinoid stems are similarly deformed.

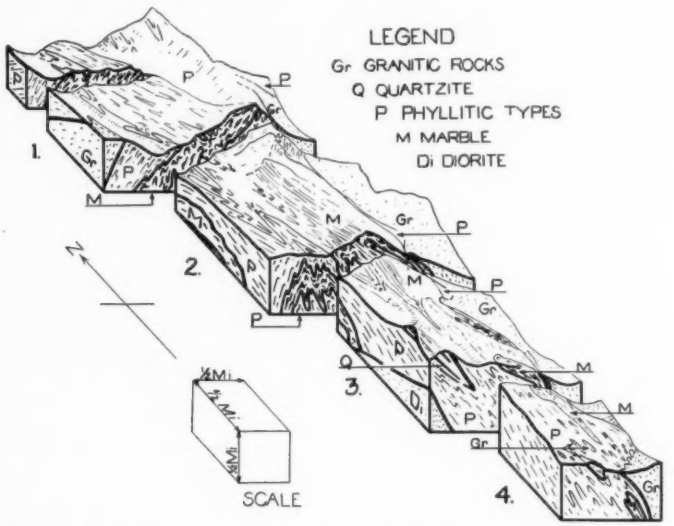


FIG. 2.—Block diagram to show structures within the septum WNW of Mount Morgan.

The meta-sediments are known to range in age from lower Cambrian[12] to Devonian.[13]

2. *Meta-volcanic rocks.*—The western part of the septum, and the entire roof remnant around Mount Ritter, are composed mainly of sheared, usually mylonitic, volcanic rocks, including basaltic, andesitic, and rhyolitic lavas, with their corresponding tuffs. Since identical rocks, occupying the same relative position in the septum farther

[12] C. D. Walcott, "Lower Cambrian Rocks in Eastern California," *Amer. Jour. Sci.*, Vol. LXIX (1895), p. 141.

[13] E. B. Mayo, "Fossils from the Eastern Flank of the Sierra Nevada, California," *Science*, Vol. LXXIV (1931), pp. 514–15.

south, have been assigned to the Triassic by Knopf,[14] it is suggested that the meta-volcanics in this area are also Triassic.

In some places a rough bedding, marked by sheared tuff partings, can be seen in these rocks. Such structure is difficult to follow, whereas a distinct schistosity, especially well developed in the pyroclastic members, is almost everywhere present. For this reason, the dip and strike of schistosity rather than bedding was mapped. Because of intense folding, the picture gained by plotting the attitude of cleavage in the meta-volcanics is strikingly similar to that obtained from bedding in the meta-sediments.

Stretching is well developed in most of the meta-volcanics, but especially so in the meta-tuffs near igneous contacts. Fragments in these pyroclastic rocks have been stretched into flattened spindles.

PLUTONIC ROCKS

The earliest intrusions (basic forerunners) in the roof remnant around Mount Ritter are composed mainly of diorite-porphyry and andesine-diabase.[15] The small, much elongated, basic intrusion in the southern part of the septum is hornblende diorite. In the roof remnant the basic forerunners are locally replaced by micropegmatitic granite.[16] This replacement may have been caused by hydrothermal solutions which rose into the roof from cooling magma below.

Following the emplacement of the basic forerunners was the intrusion of the huge massifs, and of the lesser granitic bodies within the septum. The great massifs, instead of being simple units, are each made up of a number of lesser intrusions that differ slightly in age and composition. Contacts between these lesser units are mostly sharp, and the age relations clear, but at times the interval between successive impulses has been so short that gradations result. The composition ranges from granodiorite, through even-grained and porphyritic quartz-monzonite, to aplitic granite; and the intrusions were emplaced in order of increasing silicity.

[14] *Op. cit.*, pp. 58–59.

[15] H. D. Erwin, *op. cit.*, pp. 33–38.

[16] *Ibid.*, p. 43. Erwin notes, however (p. 44), local evidence which seems to indicate that a later magma (now represented by micropegmatitic granite?) forcefully intruded the basic forerunners.

THE PROBLEM OF EMPLACEMENT

In order to discuss the problem of emplacement, it is necessary to consider the level of exposures, the relation of the intrusive masses to pre-existing zones of weakness in the wall rocks, tectonic features of the "granites," and structural modifications imposed on the wall rocks by the intrusions. The problem of emplacement leads naturally to the question of the time of intrusion in relation to the time of folding.

THE LEVEL OF EXPOSURES

Erwin's suggestion that the area around Mount Ritter is a remnant of the irregular roof of the central massif[17] can only mean that in this region erosion has not exposed a very low level in the intrusive body. This suggestion is supported by the nature of the metamorphism of the wall rocks. In general, the thermal metamorphism has been of low grade, as noted previously, but cataclastic effects are intense and widespread. With local exceptions, restricted to the immediate vicinity of igneous contacts, the marbles appear to have been the only rocks to yield mainly by recrystallization. It is evident, therefore, that the surface now exposed represents a relatively high level, where adjustment took place mainly by crushing and shear. Since so little of the roof is preserved, however, this level must be appreciably deeper than the surface now revealed in the Boulder batholith, Montana.[18]

FUNCTION OF WEAK ZONES IN THE WALL ROCKS

1. *Influence of zones of weakness parallel to the regional trend of folding.*—As is usually the case wherever intrusions have risen into strongly folded belts, most of the granitic masses in this area are elongated parallel to the regional trend of folding. On the map this is best shown by the orientation of minor intrusions within the septum and by the manner in which granitic lobes project into the metamorphic rocks along the strike of the cleavage. The lateral contacts of the larger masses for the most part parallel the regional trends.

2. *Influence of shear zones inclined to the trend of folding.*—The in-

[17] H. D. Erwin, *op. cit.*, p. 19.

[18] F. F. Grout and R. Balk, "Internal Structures in the Boulder Batholith," *Geol. Soc. Amer. Bull.* 45 (1934), pp. 877–96.

trusion between the two sharp termini in the southern part of the area has clearly been emplaced along a shear zone which traverses the strike of the folds at a considerable angle. As a result, the northern contact of this granitic mass is discordant for a distance of several miles. It is probable that similar but less pronounced zones of shear may have exerted some influence on the shapes of neighboring masses.

Obviously, the magma sought out the weakest places in the metamorphic rocks. It now remains to inquire whether the magma ascended passively by some process of assimilation or stoping, or whether it rose with force. This question makes necessary a consideration of some tectonic features of the "granites."

TECTONICS OF THE "GRANITES"

Contacts and inclusions.—Sharp, steep contacts between intrusions and wall rocks are characteristic, but locally the dip of the contact may be low, as shown in Figure 2. As a rule there is little or no change in the appearance of the granitic rock as the wall is approached, but, at a few localities in the Mount Ritter region, certain narrow marginal zones exist which may be due to assimilation.[19] The amount of assimilation indicated is, however, too small to be of importance in the problem of emplacement.

Shattering and brecciation of the walls is not uncommon. Near the wall rock the "granite" is often filled with angular xenoliths, ranging in size from a few inches to many feet. These xenoliths show very little evidence of assimilation. Such recognizable fragments of the metamorphic rocks are extremely rare far within the intrusions. Even at the present high level of exposures, by far the greater part of the "granite" is free from inclusions that might have been stoped from the roof or torn from the walls. If stoping was ever active and widespread in this region, it must have been confined to a level still higher than the one now exposed, and the evidence has been almost completely destroyed by erosion.[20]

[19] H. D. Erwin, *op. cit.*, p. 40.

[20] Locally, near the southern margin of the Mount Ritter roof remnant, Erwin (*op. cit.*, p. 38) found areas of granitic rocks containing large fragments of the metavolcanics. These xenoliths may have been stoped from the roof, but the possibility is not precluded that they have suffered little displacement or have even been carried upward.

Distributed more or less uniformly throughout the even-grained quartz-monzonite, but rare in the porphyritic variety and practically absent in the aplitic granite, are countless thousands of small dark ellipsoidal enclosures, averaging one to six inches in length. These little bodies are composed largely of femic minerals, similar to those more sparsely developed in the surrounding rock. Such enclosures might be regarded as advanced stages in the digestion of xenoliths, did not the careful work of Pabst[21] disclose a lack of gradation between these autoliths and recognizable fragments of the metamorphic rocks. Pabst leaves the origin of the autoliths an open question, but more recently Nockolds[22] on the basis of his studies of English examples has suggested that the dark enclosures are reconstituted fragments of basic igneous rocks carried up from depth. In the area under discussion this suggestion receives support from the facts that the early forerunners of the batholiths were basic and the autoliths are more or less regularly oriented, as though by differential motion in rising viscous magma.

Flow structures.—The nature and origin of structures developed by flow in viscous magma have recently been well discussed in English.[23]

The dip and strike of flattened autoliths, platy xenoliths, tabular feldspar phenocrysts, platy schlieren, and biotite booklets in the granitic rocks define the attitudes of the flow planes; these are shown on the map at localities that have been studied in sufficient detail. Within the intrusions the flow layers are vaguely marked, because in such situations the amount of differential motion in the magma has been small; but the orientation of planar elements is quite pronounced near contacts, which they tend to parallel in both strike and

[21] Adolph Pabst, "Observations on Inclusions in the Granitic Rocks of the Sierra Nevada," *Univ. Calif. Dept. Geol. Bull. 17* (1928), p. 358.

[22] S. R. Nockolds, "The Contaminated Granite of Bibette Head, Alderney," *Geol. Mag.*, Vol. LXIX (1932), p. 450.

[23] Robert Balk, "Structural Geology of the Adirondack Anorthosite," *Min. u. Petrog. Mittheilungen*, Vol. XLI (1931), pp. 314–40; "Viscosity Problems in Igneous Rocks," *Jour. Rheology*, Vol. III (1932), pp. 461–78; "Geology of the Newcomb Quadrangle," *N.Y. State Mus. Bull. 290* (1932), pp. 24–30; Ernst Cloos, "Structural Survey of the Granodiorite South of Mariposa, California," *Amer. Jour. Sci.*, Vol. XXIII (1932), pp. 289–304.

dip. The frictional drag of relatively stationary walls on the rising magma accounts for the more conspicuous development of flow planes along the margins of the intrusions. In the smaller masses, which probably did not rise so far as their larger neighbors, the development of flow planes is poor at best, even near contacts.

The pitch of long axes of spindle-shaped autoliths, of linear groups of inclusions, or of prismatic crystals of hornblende, reveals the attitudes of the flow lines. Like the flow planes, the flow lines are best developed near contacts. The pitch of the linear elements of the "granites" is often paralleled across the contact by the pitch of stretching in the metamorphic rocks. Since the flow lines indicate the direction of most rapid magma movement, it seems that friction along the walls together with side pressure has caused the metamorphic rocks to stretch in the direction in which the magma was rising. For the sake of simplicity, neither flow lines nor stretching are plotted on the map, but many hundreds of readings indicate that, in general, the intrusions have risen almost vertically.

Marginal joints and dikes.—In the incipient solid stage of an intrusion the drag of wall rocks produces inclined tension joints, which dip into the massif. These joints may extend a short distance into the wall rock and are usually filled with aplite. The significance of such marginal features ("feather joints") has recently been discussed by Cloos.[24] They indicate that the upward motion in the plastic phase, recorded by the flow lines, was continued to some extent into the incipient solid stage.

In this area the marginal joints are not always evident from casual inspection, but careful observation shows that they are developed to some extent almost everywhere along the contacts. In some places the marginal aplites are strikingly displayed, as, for example, on the western side of the septum near its southwestern terminus.

MODIFICATION OF WALL ROCK STRUCTURES BY THE INTRUSIONS

The tectonic features of the intrusions furnish a picture of viscous masses rising forcefully into the older rocks. If this is a true picture, then the formations which once filled the space now occupied by the

[24] Ernst Cloos, "Feather Joints as Indicators of the Direction of Movements on Faults, Thrusts, and Magmatic Contacts," *Proc. Natl. Acad. Sci.*, Vol. XVIII (1932), pp. 387–95.

"granites" must have been thrust aside and forced upward. This conclusion can be tested by considering certain structural modifications in the wall rocks. Unfortunately, when dealing with such enormous masses in a region where so little remains of walls and roof, it is not possible to solve the space problem quantitatively. Nevertheless, the tattered remnants of the invaded formations do furnish conclusive evidence that the metamorphic rocks were forcefully thrust aside, and this evidence must now be reviewed.

FIG. 3.—View SE, across the canyon of Convict Creek. Cliff in center of photograph is northern end of block 1, Fig. 2. Wall rock has ridden NE and upward over a sole of relatively plastic marble (*m*). Drag folding appears in the banded rocks under the thrust plane (heavy black line); *p*, phyllitic and mylonitic rocks. Broken line is contact of phyllitic rocks with marble. *X* and *Y* are points common to Figs. 3 and 4.

1. *Spreading and crowding of the wall rocks.*—Local changes in the strike of cleavage and bedding in the metamorphics clearly indicate that the minor intrusions within the septum have spread their walls apart. The structural trends are roughly molded to the shapes of these igneous bodies. An instructive example of the deflection of such trends occurs at the blunt end of the long narrow intrusion in the southern part of the septum. Here the regional strike of cleavage in the meta-volcanics is locally bent at right angles, and even the Triassic-Paleozoic contact is buckled.

The more closely adjacent intrusions approach one another, the

more severely the septum is deformed. This is well illustrated at the two southern termini. At these points the septum, reduced to a width of only a few feet, appears to have acted as a highly plastic body. A distinct linear parallelism is developed and pitches vertically. Beyond the termini, occasional intensely deformed fragments are all that remain of wall rocks that have been squeezed out between adjacent massifs.

2. *Thrusting effects between neighboring intrusions.*—The structural relations within a septum are magnificently displayed between the Mount Morgan mass and the narrow, blunt-ended intrusion about 2 miles farther west. The structure of the wall rock between these two intrusions is indicated on the map, and is also shown in Figures 3 and 4, and in the block diagram, Figure 2. In the northern block of Figure 2, the metamorphic rocks have been thrust northeastward, ahead of the western intrusion. Figure 3 is a photograph showing the thrust plane. In block 2, Figure 2, the crowding aside of wall rocks by the Mount Morgan intrusion becomes apparent; the septum is clearly squeezed from both sides. In blocks 3 and 4, the wall rocks are strongly thrust toward the northwest, and locally, marginal portions of the Mount Morgan intrusion overlie the metasediments (Fig. 4). This crowding outward from the intrusions is good evidence of the ability of rising magma to force aside the walls. Similar evidence of forceful emplacement may be found in the septum throughout the area.

3. *Thrusts along western margin of roof remnant.*—Erwin has mapped an interesting series of thrusts along the western margin of the roof remnant around Mount Ritter;[25] these thrusts are indicated on the map accompanying this paper (Fig. 1). They dip westward toward the central massif at angles varying from 30 to 70 degrees. Along one of them the amount of displacement was estimated at several thousand feet. At one locality a series of thrust slices has piled into a gap between two basic forerunners, which appear to have acted as resistant buttresses. It seems to the present writer that these thrusts were developed in response to the demand for space to accommodate the central massif.

[25] H. D. Erwin, *op. cit.*

4. *Tilting and buckling of folds.*—The shear zone along which the Mount Morgan intrusion rose has been opened locally more than 3 miles. One result has been the tilting and buckling of folds traversed by the northern contact. A few readings of the pitch of these folds are plotted on the map. Many of the folds pitch steeply under the intrusion; many more pitch away from the igneous contact, as though they have been forced upward by the rising magma; two minor folds were found to pitch vertically.

FIG. 4.—View NW from a point about three miles SE of that from which Fig. 3 was taken. Wall rocks and "granite" (*g*) have ridden WNW over the marble (*m*); *p*, phyllitic rocks and mylonite. Broken line marks contacts. View includes eastern side of blocks 2 and 3, Fig. 2. *X* and *Y* are points common to Figs. 3 and 4.

About 1 mile south of Silver Lake, a small intrusion traverses the trend of folding for a short distance. Folds in the wall rocks have been tilted steeply, the axes pitching 43 to 49 degrees away from the discordant contact.

5. *Increase in intensity of deformation near igneous contacts.*—At many places in the area it has been noticed that the wall rocks are deformed most near an igneous contact. For instance, southwest of Silver Lake near no intrusive mass basic tuffs in the meta-volcanic series contain little-deformed fragments. As these tuff bands are traced toward an intrusion, the fragments become increasingly deformed and finally disappear in the mylonitic matrix. Near the con-

tact of the central massif in the southern part of the area, a pronounced linear stretching is developed in the meta-volcanics.

In the meta-sediments the proximity of an igneous contact is often indicated by increasing mylonitization, sometimes accompanied by pronounced stretching. In addition, cleavage is usually intensified near igneous contacts, but in some cases the strongly crushed wall rocks have so recrystallized as to appear almost massive.

The five features noted above are in harmony with the idea of forceful emplacement. Thus the wall rocks furnish confirmatory evidence of the process suggested by the internal structure of the intrusions. It seems that most of the space now occupied by these igneous masses must have been won by thrusting aside the wall rocks and forcing them upward. Doubtless the entire region above these huge massifs was domed upward as the magma rose into place.

THE TIME OF INTRUSION

Since the intrusions were forcefully emplaced, it seems reasonable to suppose that during the period of folding the magma was driven upward by orogenic pressure. There are, however, two lines of evidence to indicate that the magma rose after folding was essentially completed.

1. *Relative age of the cleavage.*—As noted before, both schistosity and bedding are roughly molded to the outlines of the intrusions. Cleavage does not fit the details of the igneous contacts any better than does the bedding. Wherever a contact is disconformable, it traverses both bedding and schistosity. It is suggested, therefore, that the intrusions did not produce the schistosity but merely displaced and locally intensified it.[26] Accordingly, the cleavage was produced by orogenic forces, and its development seems to have been completed before the intrusions appeared.

2. *Relation of flow planes to regional structural trends.*—As previously stated, the flow planes are developed best near contacts because of frictional drag on rising, viscous magma. Obviously, such structures can only be explained as the result of differential motion in a fluid mass charged with crystals and inclusions.

[26] Blackwelder and Baddley (*Geol. Soc. Amer. Bull. 36* [1925], p. 209) suggest that discordant contacts may be characteristic of the higher levels of batholiths, although at depth the intrusions may produce a peripheral schistosity in their walls.

If this differential motion were the result of lateral compression, it would seem that the flow planes should always parallel the regional trends. Instead, the strike of flow planes is definitely related to the frequently changing trends of the contacts. Within the Mount Morgan intrusion, the strike of flow planes forms arcs that traverse the regional trends—an impossible condition if the differential motion were produced by intense lateral compression at this relatively high level. A regional orientation of flow planes should persist to the centers of the intrusions if the magma were strongly squeezed while cooling at this level. Actually, the central portions of the granitic bodies are almost massive; such planar trends as can be found there are vague and confused. Where flow planes parallel the regional trends, this condition is probably due, not to lateral compression, but to control exerted by zones of weakness that parallel the regional trend of folding. The magma has had to adapt itself to these weak zones.

The two lines of evidence, furnished by relation of cleavage to discordant contacts and by the arrangement of flow planes, are in complete agreement; and they clearly indicate that the intrusions appeared at or near the end of the orogeny—or were post-orogenic. In neither case is the existence of residual deep-seated compression precluded, although it would most probably exist near the end of the orogeny. Such a compressive force may have squeezed the magma upward. This force could also be transmitted hydrostatically through the molten fluid and produce the thrusting observed in the wall rocks at higher levels. On the other hand, it may be that forceful emplacement results from the natural tendency of a light, fluid body to seek its proper isostatic level. Some combination of deep-seated compression and isostatic rise is another alternative. The writer has no direct evidence which would permit a choice between these possibilities.

CONCLUSIONS

In this area a number of igneous intrusions[27] have risen almost vertically into a series of steeply dipping, intensely folded rocks.

[27] At the level now exposed, each intrusion is a separate tectonic unit, but this does not preclude a common root at depth.

The invaders were guided by zones of weakness, usually parallel to the regional trend of folding but occasionally inclined to it.

The amount of assimilation indicated by hybrid border zones is very limited; and the almost complete lack of recognizable wall rock xenoliths, except in the immediate vicinity of contacts, would seem to indicate that stoping has not been a major factor in the mechanics of emplacement.

The internal structures of the intrusions and the presence of basic enclosures thought to have been carried up from depth indicate that these igneous masses have been forcefully emplaced. Externally, the same forceful emplacement is demonstrated by structures imposed on the metamorphic rocks subsequent to folding.

Obviously, when dealing with such huge units, it is not possible to demonstrate that the amount of thrusting and doming of the metamorphics has been sufficient to provide all of the needed space, but the great importance of these mechanical processes is clearly revealed by the field evidence.

At the level now exposed, folding and attendant production of cleavage were at least essentially completed before the intrusions appeared.

ACKNOWLEDGMENTS.—For funds which made the field work possible, the writer wishes to thank the California State Division of Mines and the National Research Council. Drs. Ernst Cloos, Robert Balk, and C. M. Nevin have offered valuable suggestions concerning the problems involved, and their kindness is greatly appreciated. The writer assumes all responsibility, however, for the views presented in this paper. Sincere appreciation is extended to Messrs. L. C. Conant and J. R. Chelikowsky, who ably assisted in the field during the past summer. Finally, it is desired to acknowledge the kindness of Mr. H. D. Erwin, who placed at the writer's disposal the results of a three-year study of the geology of the area around Mount Ritter.

BASIN-RANGE FAULTING OF 1915 IN PLEASANT VALLEY, NEVADA

BEN M. PAGE
Stanford University, California

ABSTRACT

Fault scarps of at least three ages are found on the eastern side of Pleasant Valley, Nevada. Of these, the most recent were formed in 1915, when a displacement occurred along the western base of the Sonoma Range. Two fault blocks rose relative to the adjacent valley, producing low scarps at the foot of the mountains. The movement was a dip-slip displacement on normal faults which trend north and northeast.

INTRODUCTION

The Pleasant Valley earthquake of October 2, 1915, received much attention both because it was of major intensity and because it resulted from displacements which reached the surface of the earth. Some of these displacements were mapped by the author and are the principal subject of this article. They had previously been described in part by the late Dr. J. C. Jones[1] and by S. L. Berry,[2] and have been alluded to by many others.

PLEASANT VALLEY AND THE SOUTHERN SONOMA RANGE

Pleasant Valley is in Pershing County, north-central Nevada, and is best reached by a road which proceeds southward from Winnemucca. The valley is an elongated, north-south depression between the Sonoma Range (on the east) and the East Range, its dimensions being roughly 5×25 miles. The valley floor, which is estimated to be about 4,300 feet above sea level, is in part a playa. From this flat area, overlapping alluvial fans rise gradually to the bases of the mountain ranges on either side; at their juncture with the Sonoma Range are the recent fault scarps described below. The alluvium diminishes in thickness at the south end of Pleasant Valley and gives way to a pediment cut in tilted Tertiary rocks of volcanic, fluviatile, and lacustrine origin.

[1] J. C. Jones, "The Pleasant Valley, Nevada, Earthquake of October 2, 1915," *Seism. Soc. Amer. Bull.* 5 (1915), pp. 190–205.

[2] S. L. Berry, "An Earthquake in Nevada." *Mining Sci. Press*, Vol. CXIII (1916), pp. 52–53.

The general region is characterized by fairly youthful basins and ranges. The portion of the East Range adjacent to Pleasant Valley

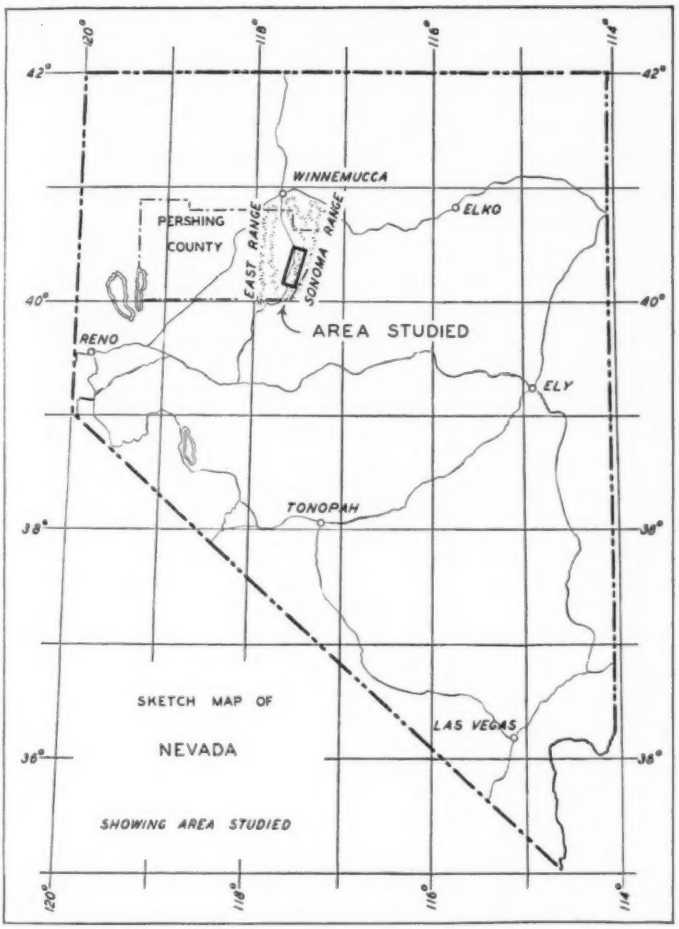


FIG. 1.—Sketch map of Nevada

presents a somewhat subdivided lava cap which slopes gently eastward and perhaps extends beneath the valley sediments. The nearby

Stillwater Range to the south has a steep and impressive eastern escarpment, while the western slope is comparatively gentle. The Star Peak Range, to the west, has a western escarpment and a faulted bajada at the north end. The Humboldt Lake Range, about 45 miles to the west of Pleasant Valley, has pronounced fault-block characteristics.[3] To the east, the Battle Mountain Range is in topographic accord with the foregoing examples. All of these ranges show escarpments, which, although not so youthful as many others in the Basin-Range province (notably those in southern Oregon), are nevertheless not extensively embayed by erosion.

The Sonoma Range[4] itself is similar to its neighbors in many respects. Like most of the nearby ranges, it consists of several parts that are distinct both structurally and physiographically. Only the southern portion is treated here. This portion is composed principally of two fault blocks, which in this paper are designated as the "Tobin block" and the "Pearce block." Their relation to each other is shown in Figure 2.

THE TOBIN BLOCK

The Tobin block is a high north-south ridge about 9 miles long and 4 miles wide, attaining an elevation of 9,779 feet at the summit of Mount Tobin. It is partly made up of pre-Tertiary rocks, the age of which is unknown. These rocks include quartzites, phyllites, grits, limestone, and shale. The sedimentary beds are considerably folded and are locally intruded by dikes of andesite and rhyolite. No lava cap exists on the Tobin block.

The horst nature of the block is indicated topographically (Fig. 2). The Pleasant Valley side and the Buffalo Valley side are both eroded escarpments that consist partly of alined facets sloping about 26°.

The Tobin block has been dissected to maturity. The canyons, which are youthful, terminate in V-shaped mouths, emptying out upon fans which locally slope as much as 7° but which are mostly less steep. On the western side of the block the juncture of mountain and fan is at a very high level (Fig. 2). The western fans are incised by

[3] G. D. Louderback, "Basin Range Structure of the Humboldt Region," *Geol. Soc. Amer. Bull.* 15 (1904), pp. 289–346.

[4] The Sonoma Range is designated by King as the "Havallah Range" (C. King, *U.S. Geol. Explor. 40th Parallel*, Vols. I and II [1878]).

gullies 50 or 60 feet deep which are continuations of the canyons in the mountains. Possibly fault movements have been smaller or less frequent than formerly and the fans are doomed to complete dissection. On the other hand, it is possible that the margin of the valley is clinging to the rising mountains and that elastic rebound may eventually restore it to its original position.

The fault which bounds the Tobin block on the west is (in this paper) called the "Tobin fault." It was active, in part, at the time of the Pleasant Valley earthquake of 1915.

FIG. 2.—The southern part of the Sonoma Range. This shows the Tobin block and an end view of the low Pearce block. At the base of each is a fault scarp of 1915 origin, too distant to be visible. The fresh scarp of the Pearce block would appear as a point at the foot of the slope at the right-hand edge of the picture, as it proceeds directly away from the observer.

THE PEARCE BLOCK

The Pearce block is a low, wide fault block adjoining the Tobin block on the south and southwest (Fig. 2). It trends about N. 20° E. and is over 20 miles long and 5 miles wide. Parts of it consist of rocks similar to those of Mount Tobin. Other parts are folded Mesozoic marine quartzites and dolomites which are overlain unconformably by a thick Tertiary (presumably) volcanic series including rhyolite, andesite, and basalt, together with agglomerates and tuffs. A volcanic neck is exposed at the mountain front just north of Pearce's ranch.

The Tertiary volcanic rocks do not occur as a continuous cap, but for the most part dip eastward in a series of hogbacks and cuestas. They are locally repeated by faulting. Either these rocks are part of an anticlinal limb or they have been tilted by faulting parallel to the trend of the range; their strike is roughly that of the mountains.

In the Pearce block a few of the canyons which empty into Pleasant Valley contain small aggraded flood plains in their lower courses. These plains have been trenched, owing to the 1915 rejuvenation. One or two sets of terraces are discernible above the last plains, suggesting earlier rejuvenations of the same order of magnitude as the movement of 1915.

The western side of the Pearce block is an escarpment similar to that of the Tobin block, except that facets make up more of the mountain front. Flanking this escarpment are alluvial fans which are not deeply cut by gullies except where headward erosion has proceeded from a rather recent canyon draining Pleasant Valley to the south.

The eastern side of the block does not resemble the western side, as the mountains slope down to a dissected pediment in Jersey Valley. The pediment is cut in Tertiary rocks which are partly tuffaceous shales in lacustrine beds. The absence of fans and fault-scarp features indicates that the Pearce block is being tilted eastward, the Pleasant Valley side being the (relatively) rising portion.

The fault bordering the Pearce block on the west was active at the time of the Pleasant Valley earthquake; it is here called the "Pearce fault."

THE OLDER FAULT SCARPS OF PLEASANT VALLEY

Fault scarps of at least three ages are situated on the eastern side of Pleasant Valley near or at the juncture with the Sonoma Range.

The oldest scarps include much of the front of the southern Sonoma Range: the western sides of the Tobin block, the Pearce block, and a southern continuation of the latter, which is offset a mile or two to the east. The last-mentioned scarp was not augmented by the uplift of 1915, but the other two rise above fresh scarps which resulted from that movement. The older scarps mostly consist of large facets which are separated by V canyon mouths. The facets were not observed to slope more than 30°, even at the base, which in most cases is steeper than the upper portions. They do not extend entirely to the crest of the mountains. They are alined, but in an irregular rather than a straight line. In a few places the alinement is broken by small salients which are step blocks (Fig. 5).

More recent than the oldest scarps are a few low escarpments in the bajadas and pediments at the north and south ends of Pleasant Valley. These features trend roughly parallel to the Sonoma Range, but lie a mile or so to the west of the mountains. For the most part they do not exceed 20 feet in height, and now appear as gentle slopes. There is some similarity to shore lines, but the fans are transected rather than contoured. (No shore lines of Pleistocene lakes were observed in Pleasant Valley.) In a few places the fan scarps and pediment scarps have been slightly augmented by displacements of 1915. These scarps on the whole cannot be considered as old as much of the mountain front, as they consist of alluvium and must therefore be comparatively short-lived.

THE SCARPS OF 1915

The fault scarps of 1915 are the most notable geological feature of the region. Only the scarps of Pleasant Valley are here described; but contemporaneous displacements occurred in Pumpernickle Valley along a branch of the Sonoma Range to the northeast, and in the Stillwater Range to the south. These localities have not yet been fully studied.

The course of the fresh scarps.—The course of the fresh scarps in Pleasant Valley is shown on the accompanying map (Fig. 3). There are two main scarps, belonging to the Tobin fault and the Pearce fault, respectively, and they will be designated by the names of these faults. They closely follow the older escarpments forming the mountain front.

The Tobin scarp does not occupy the entire length of the Tobin fault. At the south end of this fault, where the two fault blocks join, the Tobin scarp dies out while the fault continues. The northern extremity of the Tobin fault was likewise inactive in 1915. Near the northern end of the active portion, another small scarp of 1915 parallels the Tobin scarp, following one of the older scarplets in the bajada.

The Pearce scarp, on the other hand, occupies the entire length of the Pearce fault. Near the south end of Pleasant Valley the Sonoma Range is sharply offset a mile or so to the east. The Pearce scarp does not follow the offset, but continues southwest along a low eroded scarp in the pediment for 2 miles before coming to an

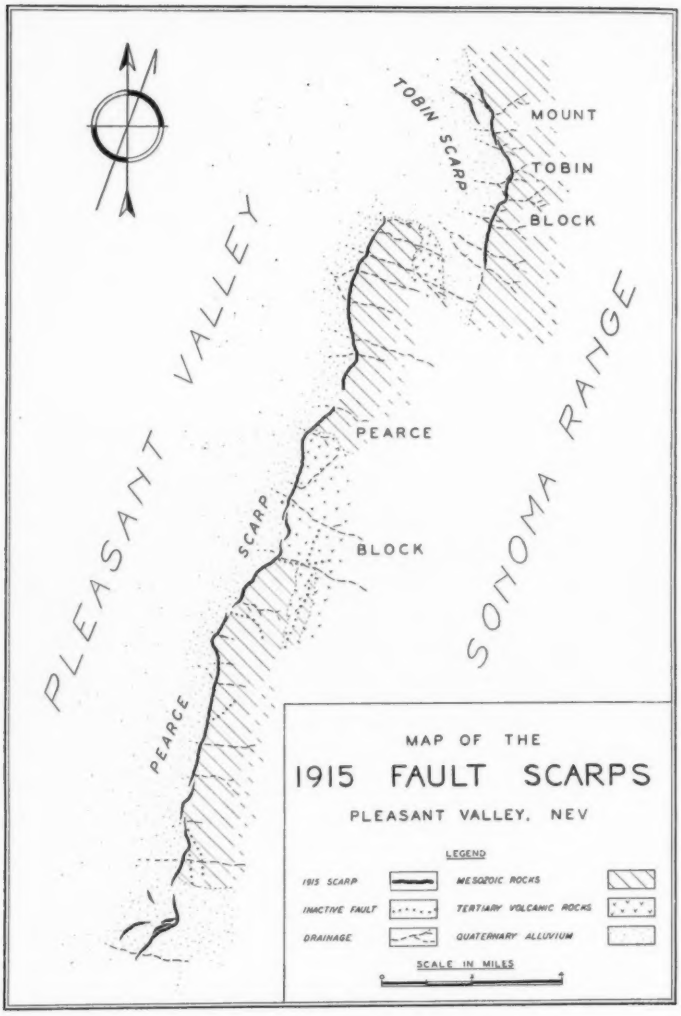


FIG. 3.—Map of the 1915 fault scarps

end. The pediment here is also the site of other small scarps of 1915 origin, these being independent of the Pearce scarp.

The Tobin scarp is oriented nearly north and south, while the Pearce scarp trends about N. 20° E. As shown on the map, they are far from straight, making several large deviations and innumerable small ones of the order of 50 feet or so. As the scarps do not consistently deviate either upstream or downstream where canyons are crossed, their relation to the topography does not reveal the dip of the faults.

FIG. 4.—The Pearce scarp. This fresh scarp (appearing as a white line in the picture) was formed in 1915 at the foot of the older, eroded fault scarp which constitutes the mountain front.

The Tobin scarp rises gradually toward the south, while the Pearce scarp maintains a more nearly constant elevation. Both sink abruptly where canyons and gullies are crossed, and in some other situations climb a short distance above the foot of the mountain.

The two main scarps are almost continuous, though interrupted in a few places. Also, each has locally small branches and short parallel scarps which are prominent where the rock is very weak, as in the neighborhood of an inactive transverse fault (Fig. 5).

Dimensions.—The Tobin scarp is 4.6 miles long and varies in height from 0 to about 10 feet, dying out gradually at both ends.

On the bajada at the north end of Pleasant Valley, the fresh fan scarp is from 0 to 3 feet high.

The Pearce scarp is 16.7 miles long and ranges up to 16 feet in height near the middle of its length. On the pediment at the south end of Pleasant Valley, the Pearce scarp is from 0 to 5 feet high and the smaller ones attain 4 feet or less.

As a group the 1915 scarps in Pleasant Valley are 21.3 miles long, disregarding curves; yet the variation in height is only 16 feet throughout a distance of 112,644 feet (a variation of 1 in 7,040).

FIG. 5.—The Pearce scarp, showing its behavior where an inactive transverse fault is transected. Note also the two step blocks at the right.

The height of the scarps at any one point is not a true measure of the fault displacement because the scarps are steeper than the faults, as will be explained below.

Other features of the fresh scarps.—The fresh scarps are mostly vertical, or nearly so, though in places eighteen years of erosion have somewhat modified the original steepness. The fault surfaces are rarely seen because, for the most part, only alluvium is exposed. This alluvium, clinging to the fault surfaces, has produced the vertical escarpments, masking the true fault dip and permitting a superficial branching of the scarps (Figs. 6 and 7).

Slickensided dolomite is exposed by the Pearce scarp at one place

and shows the fault dip to be 49° W. at that point (Fig. 8). At another place, where the same fault traverses the pediment at the

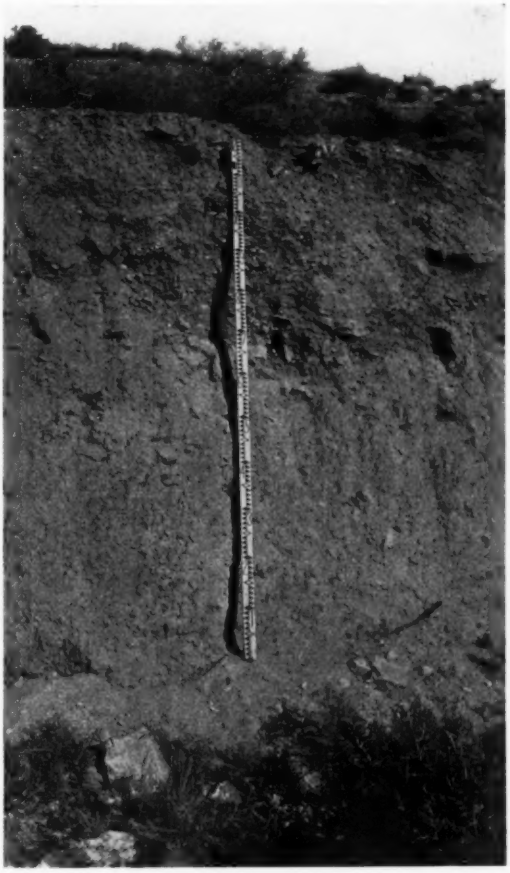


FIG. 6.—Close-up of the Pearce scarp, showing its composition and its height near Pearce's ranch. No bedrock is exposed. (The stadia rod is 12 feet long.)

southern end of Pleasant Valley, the actual caliche-covered fault surface is shown (Fig. 9) and here dips from 75° to 81° W. Elsewhere

the true dip can be ascertained only where canyons cross the scarps and reveal the true fault profiles (Fig. 10).

Near several of the canyons the fault scarps are accompanied by a trench, perhaps 10 feet wide and 10 feet deep (Fig. 11), which lies at their foot. This feature is due to the fact that the footwall carried adhering alluvium relatively eastward as well as upward (Fig. 7).

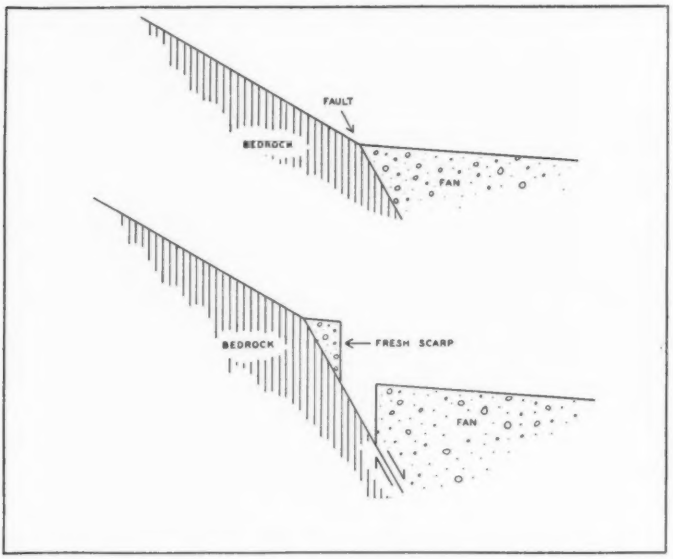


FIG. 7.—Relation of fresh scarp to the fault surface

In most places no single trench follows the scarps, but at the base of the latter the ground appears to have been torn up by an immense plow. In other places alluvium has settled into miniature grabens adjacent to the scarps. These features originated in about the same manner as the "plowed" areas.

Many different kinds of rock were cut by the faults. For the most part the behavior of the latter was not greatly affected by the type of rock at any one point, although the scarps are subdivided most where the material is weakest. In two places the Pearce scarp swings about 1,000 feet to the west in a broad arc, then returns to its

former course. The northernmost arc of this sort is a mile or so north of Pearce's ranch. Here a Tertiary volcanic neck, which is harder

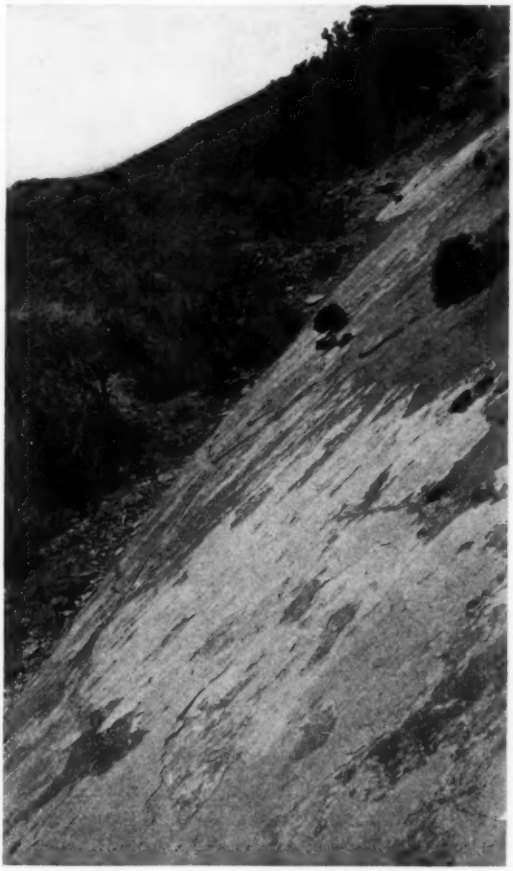


FIG. 8.—Fault surface dipping 49° W. In this one instance bedrock constitutes the Pearce scarp. The rock is slickensided dolomite, covered with caliche.

than the adjacent rock, makes up the mountain front and may be supposed to have deflected the course of the fault. However, the

FIG. 9.—The Pearce scarp in alluvium at the south end of Pleasant Valley. The caliche-covered fault surface, exposed by the 1915 displacement, dips 75°–81° W.

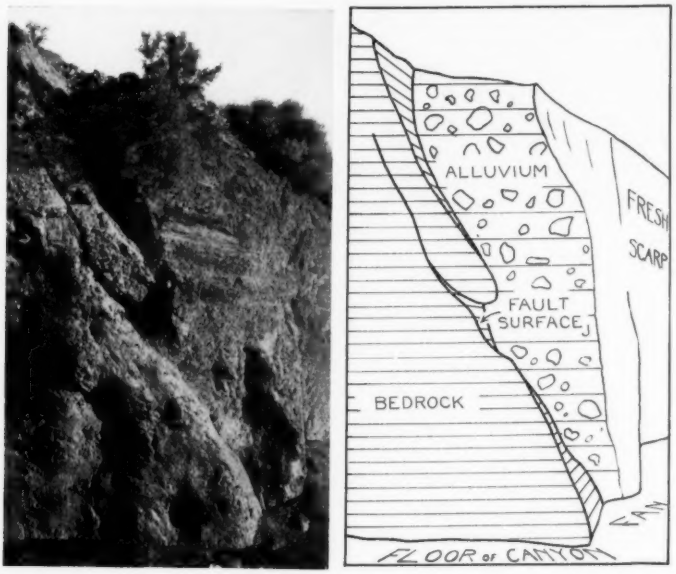


FIG. 10.—Cross section of the Pearce fault and fresh scarp. Fault and scarp are shown in profile at the mouth of a canyon that was deepened artificially after the uplift of 1915.

southernmost of the two great deviations is situated in dolomite which extends well beyond the "deflected" portion of the fault. Thus in this second instance, at least, the strength of the surface rock does not account for deviation in the course of the fault.

THE NATURE OF THE FAULTING

Figures 11 and 13 supply some evidence as to the nature of the 1915 movement. The displacement was in a direction parallel to the

FIG. 11.—Gap between the Tobin scarp and alluvial fan. The footwall carried some adhering alluvium upward and to the left (east), leaving a gap between it and the fan (right).

dip of the faults, which are normal. In other words, the components were vertical and about east-west. The former was between 0 and 15 feet; the latter between 0 and 13 feet. Assuming a uniform fault dip of 60° and an average throw of 10 feet, the average heave would be 5.7 feet. This figure is probably fairly representative.

Did the mountains rise or the valley sink? The answer is largely speculative, as there were no benchmarks here in 1915. The elastic rebound theory leads one to suspect that at the time of the earthquake the margins of both the mountain and valley blocks sprang into comparative equilibrium, one upward and the other downward. Mr. W. L. Pearce, whose ranch is alongside the Pearce fault, observed that water in his orchard ran sluggishly after the earthquake,

whereas previously it had run swiftly toward the bottom of the valley. This may indicate a change in slope due either to elastic re-

FIG. 12.—Pearce scarp at the base of a volcanic neck. Bedrock is not exposed here on the scarp, contrary to appearance.

FIG. 13.—The Pearce scarp, showing its form at a gully. The equally broad sides of the V indicate that practically no displacement occurred parallel to the strike of the fault when the scarp was formed.

bound or to a settling of the alluvium next to the fault. A long-continued, slow movement probably led up to the displacement of 1915, but its character is unknown.

COMPARATIVE DISPLACEMENTS

Within historical times two somewhat similar dislocations are known to have occurred in North America. In 1872 scarps were formed at the eastern base of the Sierra Nevada and the Alabama Hills in Owens Valley, California.[5] This movement, however, had a large strike-slip component and somewhat resembled that which produced the Cedar Mountain earthquake[6] of 1932 in Nevada. In 1887 a displacement left a long escarpment on one or both sides of the San Bernardino Mountains in Sonora, Mexico.[7]

TABLE I

Location	Date	Maximum Vertical Displacement in Feet	Maximum Horizontal Displacement in Feet
Assam, India*	1897	35	0
Owens Valley, California†	1872	23	12
San Andreas fault, California‡	1906	3	21
Mino-Owari, Japan§	1891	20	13
Sonora, Mexico‖	1887	20	0?
Pleasant Valley, Nevada	1915	16	1
Wellington, New Zealand¶	1855	9	0?
Honshu, Japan**	1896	6	?
Formosa, Japan††	1906	6	8
Baluchistan‡‡	1892	0?	$2\frac{1}{4}$

* R. D. Oldham, "Report on the Great Earthquake of 12th of June 1897," *Mem. Geol. Surv. India*, Vol. XXIX (1899), pp. 1–379.

† W. H. Hobbs, "The Earthquake of 1872 in the Owens Valley, California," *Beitr. Geophysik*, Band X (1910), p. 379.

‡ A. C. Lawson *et al.*, "The California Earthquake of April 18, 1906," *Rept. of State Earthquake Investigation Commission, Carnegie Inst. Wash. Publ. 87* (1909–1910).

§ B. Koto, "On the Cause of the Great Earthquake in Central Japan, 1891," *Jour. College Sci., Tokyo Imper. Univ.*, Vol. V (1892), pp. 295–353.

‖ G. F. Goodfellow, "The Sonora Earthquake," *Science*, O.S., Vol. XI (1888), pp. 162–68.

¶ C. Lyell, *Principles of Geology* (11th ed.; New York: D. Appleton & Co., 1892), Vol. II, pp. 82–89.

** A. W. Grabau, *A Comprehensive Geology* (New York: D. C. Heath & Co., 1920), Part I, *General Geology*, pp. 664–88.

†† W. H. Hobbs, *Earthquakes* (New York: D. Appleton & Co., 1907), pp. 66–67.

‡‡ C. L. Griesbach, "Notes on the Earthquake in Baluchistan on the 20th of December, 1892," *Rec. Geol. Surv. India*, Vol. XXVI (1893), pp. 57–64.

[5] W. H. Hobbs, "The Earthquake of 1872 in the Owens Valley, California," *Beitr. Geophysik*, Vol. X (1910), p. 379.

[6] V. P. Gianella and E. Callaghan, "The Earthquake of December 20, 1932, at Cedar Mountain, Nevada, and Its Bearing on the Genesis of Basin Range Structure," *Jour. Geol.*, Vol. XLII (1934), pp. 1–22.

[7] G. F. Goodfellow, "The Sonora Earthquake," *Science* O.S., Vol. XI (1888), pp. 162–68.

For comparative purposes, the Pleasant Valley movement is placed among a list of some of the most notable recent displacements that have appeared as such at the earth's surface (Table I).

A number of other slips are known to have had displacements similar in magnitude to those listed in the table. In addition there have been large changes of level which may or may not have involved the formation of definite scarps. For instance, Chile, Jamaica, Italy, and notably Alaska[8] have suffered sudden and local changes in level which seem to imply the existence of unseen scarps. However a few sudden displacements have been known to produce rising and sinking of the ground without scarps, even when the magnitude of the changes was 20–30 feet, as in the Mississippi Valley at the time of the New Madrid earthquake (1811).[9]

CONCLUSIONS

The following are some of the more important facts connected with the Basin-Range faulting of 1915:

1. The southern Sonoma Range in the locality studied consists of two adjacent fault blocks.

2. These two blocks could easily have been recognized as such prior to 1915, thus proving the validity of conventional fault scarp criteria.

3. The facets of the mountain front mostly slope less than 30°.

4. At the western base of each block is an irregular normal fault, dipping more steeply than the facets (41°–81°).

5. On October 2, 1915, the two marginal faults suffered a dip-slip displacement. There was no appreciable strike-slip component.

6. The two blocks behaved more or less as a unit during this recent movement.

7. Fresh fault scarps appeared at the immediate base of the mountains.

[8] R. S. Tarr and L. Martin, "The Earthquakes at Yukatat Bay, Alaska, in September, 1899," *U.S. Geol. Surv. Prof. Paper 69* (1912), pp. 1–135.

[9] M. L. Fuller, "The New Madrid Earthquake," *U.S. Geol. Surv. Bull. 494* (1912), pp. 1–119.

8. The fresh scarps are composed of alluvium clinging to fault surfaces that are less steep and more regular than the scarps themselves.

9. The maximum throw indicated by the fresh scarps (about 16 feet) is of the same order of magnitude as some past displacements in this locality and of quite a few historical fault movements in other localities.

ACKNOWLEDGMENTS.—This study was suggested and aided by Dr. Aaron C. Waters. Dr. Siemon W. Muller, Henry M. Page, and the inhabitants of Pleasant Valley were also of very great assistance.

KENTUCKY KARST LANDSCAPES

SAMUEL N. DICKEN
University of Minnesota

ABSTRACT

The fundamental quality of the Kentucky karst is the underground drainage developed on the Upper Mississippian limestones, a factor which makes for distinctive forms on the surface as well as great caverns beneath it. Since geologic structure controls the distribution of the different phases of the karst, and since the Kentucky karst is located on the outer margin of the Western Coal Basin, the major area in Kentucky is in the form of a rude crescent, with the early phases of the karst on the inner margin of the crescent and the later stages on the outer margin. In the first stage the surface streams, intrenched in the Chester clastics, are captured by underground drainage. The transfer of surface run-off to underground channels is followed by a change in surface forms, closed solution depressions superseding the valleys of surface streams. After the sandstones of the Chester series have been removed the entire surface is formed by solution depressions, with convex or concave slopes depending on the relative intensity of solution. When an impermeable bed is reached the depressions begin to fill with insoluble sediment, the underground channels become blocked, and surface streams begin to appear on the bottoms of the filled depressions, thus marking the end of the karst.

Southwestward from Louisville, flanking the Western Coal Basin in a broad crescent, lies the greater part of the Kentucky karst, a streamless region known since the days of settlement as the "Big Barrens" (Fig. 1). To the early explorers and settlers, accustomed to the forest, the outstanding feature of the area was the absence of trees, but today, with the greater part of the land in farms, the most distinctive quality is the variegated pattern of solution features (karst), and the absence of small streams. In contrast with the bordering hilly regions the karst is a rolling plain made up of thousands of solution depressions and intervening ridges, the relief depending on the intensity of solution, which in turn depends on the quality of the underlying rocks.

STRUCTURE AND LITHOLOGY

Various aspects of the geology and geography of the region have been incorporated in the reports of the Kentucky Geological Survey;[1] it seems advisable to recapitulate only the general geologic fea-

[1] Carl O. Sauer, "Geography of the Pennyroyal," *Ky. Geol. Surv.*, 6th ser., Vol. XXV (1927); J. M. Weller, "Geology of Edmonson County," *Ky. Geol. Surv.*, 6th ser., Vol. XXVIII (1927); A. K. Lobeck, "Geology and Physiography of the Mammoth Cave National Park," *Ky. Geol. Surv.*, 6th ser., Vol. XXXI (1929).

tures upon which the karst landscapes are based. The characteristic structural feature of the Kentucky karst is the gentle dip of the strata

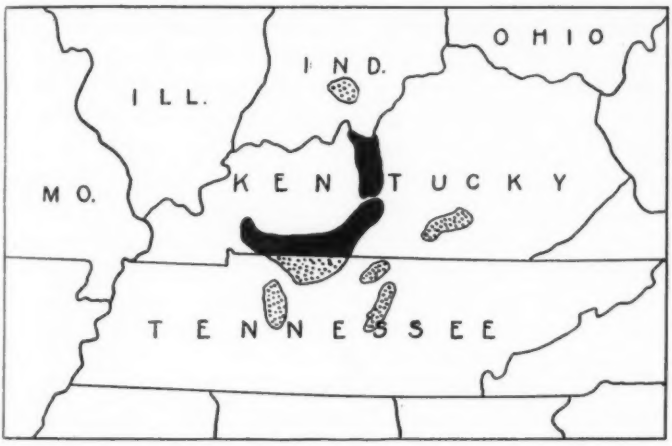


FIG. 1.—Sketch map showing the location of the Kentucky karst. The dotted areas indicate adjacent karst regions not discussed in this report.

(20–50 ft. per mile) marginal to the Western Coal Basin, which is responsible for the broad outcrop of the Mississippian formations in western Kentucky (Fig. 2). It is apparent that the structure being

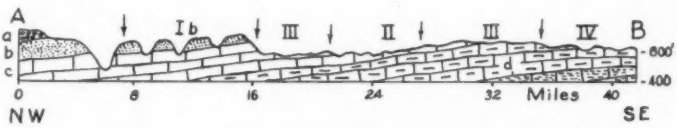


FIG. 2.—Profile section of the Kentucky karst in the vicinity of Mammoth Cave (for location see Figure 8). *a*, the Pottsville conglomerate; *b*, the Cypress sandstone; *c*, the Ste Genevieve limestone; *d*, the St. Louis limestone; the Warsaw limestone appears in the lower right-hand corner. The numerals I, II, III, and IV refer to karst phases described in the text.

synclinal, the rock formations outcrop as crescent-shaped bands marginal to the Western Coal Basin, the innermost bed being the youngest. It follows that the youngest stages of the karst are on the inner margin, and the oldest stages on the outer fringe. Further-

more, as the surface is being reduced by the karst processes, the phases are displaced down dip.

The rocks which immediately underlie the karst are all of Upper Mississippian age; and, for the purposes of this discussion, may be divided into two main groups, the Lower Limestone group (Fig. 2), generally called the Mammoth Cave series, and the Upper Clastic group, called the Chester. The Warsaw shaly limestone, below the Mammoth Cave series, is the impermeable bed which usually marks the lower limit of the karst development. No brief description of the foregoing formations will hold for their varying facies. The descriptions given here are intended to give a general idea of their more typical qualities and their most common relation to the karst. The sandstones, shales, and limestones of the Chester series border the Western Coal Basin in a belt which varies in width from 5 to 10 miles. Though the limestones of this series are not generally of sufficient thickness or purity to develop real karst morphology, there is underground circulation and erosion. The fissures are thereby enlarged, and karst-making is greatly accelerated when the circulation reaches the thick soluble limestones of the Mammoth Cave series. Furthermore, a consideration of the Chester rocks is necessary to an understanding of the pre-karst forms, since the landscapes which were developed on the Chester rocks impose some of their qualities on the succeeding landscapes.

The Cypress is a massive, medium-grained sandstone, varying in thickness from 40 to 80 feet. The degree of induration varies but is not usually high, the subangular quartz grains generally weathering readily into a medium, even-textured sand. The limestones lying underneath the Cypress sandstone, and known collectively as the Mammoth Cave limestones, aggregate more than 500 feet in thickness, and constitute the principal formations upon which the karst is developed. The upper member, the Ste Genevieve, yields more readily to solution, and for that reason develops somewhat different karst forms. The residual soils derived from the Ste Genevieve contain considerable chert, which is an important factor in karst-making.[2] The St. Louis is a fine, gray limestone with bands of nodular chert and a few isolated layers of clay. The formation is 300 feet

[2] A. M. Miller, "Geology of Kentucky," *Ky. Geol. Surv.*, 5th ser., Vol. II (1919).

thick, or more, and varies lithologically between different horizons. The Warsaw formation in western Kentucky is usually an impure limestone, the impurities consisting of shaly beds, cherty layers, and geodes. The top of the formation is a coarse, dark, bluish-gray limestone, the color forming a partial basis for distinguishing the Warsaw from the St. Louis limestone above. The chert occurs as layers or bands, generally discontinuous and usually not more than 1 foot thick, or as cherty nodules which weather out as subspherical boulders. Although the top of the Warsaw does not represent in every case the lower limit of the karst development, the base is usually not far below the contact with the St. Louis. This is true, apparently, not because the upper phases of the Warsaw are insoluble, but because fissures must be opened at considerable depth below the surface before the karst development can occur on a large scale.

KARST FORMS

Before the surface forms appear, a system of underground channels must have developed. Long before the surface streams have exposed the Mammoth Cave limestones, percolating waters have reached the fissures of the limestone and solution has begun. The sandstone above is sufficiently permeable to carry water quickly to the upper surface of the limestone. But for the joints in the limestone the water could not penetrate farther, since the limestone is almost impermeable. In order that solution may be effective, the joints must be opened, since otherwise the waters reaching the surface of the limestone would have no outlet other than by interstitial seepage. In the beginning, the joints are mere cracks, which permit only very small quantities of water to enter and seep slowly downward. Until the joints have been enlarged, the process is of necessity very slow, but is accelerated as time goes on, until the entire net of small surface streams has been captured. The minute forms which develop on the surface of the limestone resemble chiseling or carving on the surface of the rock (Fig. 3). In reality this is the "exposed" surface of the limestone, though many feet of sandstone and soil may yet cover it. These forms may be seen at the surface in railroad or highway cuts, in fact wherever the contact between rock and soil is exposed.

Granted that the water which percolates through the soil and reaches the limestone below is at least partly charged with carbon dioxide, how does it function in the decomposition of the rocks?

FIG. 3.—Fissures exposed by soil erosion in Meade County. This view shows the character of the soil-rock contact.

Aside from the wastage at the soil-rock contact, where does solution occur? Is there a lower limit below which solution is not effective? These points have divided students of the karst into two schools: the older school considering that all water below the ground-water level

is stagnant, the younger school believing that there is vigorous circulation below the ground-water level or that there is no ground-water level at all.[3]

The significance of the divergent approaches is obvious enough. If the definite ground-water level exists and the water below it is stagnant, all the solution must occur above this level. If, on the other hand, there is no stagnant ground water and circulation reaches greater depths, greater opportunity will be afforded for solution at various levels, and as a consequence a network of underground channels will be developed. A few significant observations have been made in the lowest levels of the caves, most of which are rarely accessible; some are too narrow, others are filled with water. Several, however, may be entered with ease; one of these leads down to Echo River in Mammoth Cave, an underground stream which fluctuates in height with the stages of Green River. Even in these lowest levels there is no evidence of stagnant water. The only water not in motion appears to be in pockets, below which there are, in some cases at least, open channels. And if we may accept the evidence of the subfluvial springs in Green River, there is movement of water below the level of Echo River.[4]

Once the underground drainage has been sufficiently established to engulf the upper course of a small stream, the character of the stream bed begins to change and the first karst form, the ponor[5] appears. The ponors are small, about 5 feet in diameter, have steep, almost vertical slopes, and are asymmetrical both in plan and profile. The surface development of the ponor is simple. When a portion of the stream is completely engulfed by an enlarged fissure the upper part of the stream continues to flow on the surface as far as the fissure. Here the water sinks, carrying with it such sediment as it can. The effect of the opening of the fissure is to increase the carry-

[3] For a brief history of the evolution of ideas concerning the karst see J. Cvijič, "Hydrographie souterraine et évolution morphologique du Karst," *Trav. Inst. de géog. Alpine*, Vol. VI (Grenoble, 1918), p. 376; and E. de Martonne, *Traité de géog. physique*, Vol. II (Paris, 1926), pp. 666–68.

[4] Cvijič, *op. cit.;* and E. A. Martel, *Nouveau traité des eaux souterraines* (Paris, 1921).

[5] Since local terms such as "sink," "sink hole," "kettle," "bottom," etc., are vague and confusing the Slovene terminology ("ponor," "doline," etc.) is used for the karst forms. See J. Cvijič, *op. cit.;* and E. de Martonne, *op. cit.*

ing power of the flowing water so that in its immediate vicinity much soil is removed. Sediment frequently stops the fissure, but eventually it is reopened, since even though the ponor is dammed by sediment, the surface water filters slowly through, enlarging the fissures

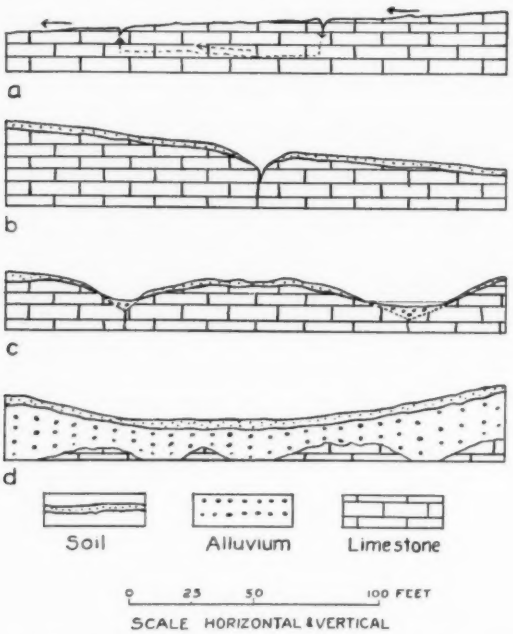


FIG. 4.—Profile sections of karst forms. *a*, profile of a small tributary of Alexander Creek in Edmonson County, showing how the stream sinks and reappears farther down the valley; *b*, profile of a young doline with open bottom; *c*, dolines partly filled by denudation; *d*, profile of a basin in Allen County constructed from observations made in the stream bed which now intersects the basin. The spaces between the rock outcrops mark the position of former dolines.

and eventually enabling the transfer of sediment through the underground channels.

As the ponor is deepened and widened it changes gradually into a doline (Figs. 4, 5, 6). The doline is more regular and symmetrical than the ponor, the bottoms of the dolines may be open or closed, and the convex slopes may vary from a few degrees to 20 degrees.

The simple doline in Kentucky is round or oval in plan, and the diameter generally does not exceed 100 feet. The existence of the do-

FIG. 5.—A young doline a few miles east of Louisville, characteristic of the early karst stages.

FIG. 6.—Following a heavy shower the bottom of this doline in Barren County is temporarily ponded. Rock fragments, exposed by soil erosion, are to be seen in the foreground.

line depends upon a well-opened underground fissure. If the fissure is short, the ground plan of the doline is nearly circular; if long, the

plan is oval. In each case the intensity of karst-making is greatest at the fissure and less on the periphery of the doline. Hence the convexity of slope, if the karst-making processes are more important than denudation (Fig. 4). In any case denudation plays an important rôle. Its function is to reduce the steep slope which develops at the fissure. The relative intensity of the two processes—solution and denudation—is an important index of slope in the Kentucky karst.[6]

When the dolines have developed their normal profile and plan, they may be altered by the coalescing of other karst forms. When the process of denudation has reduced the sides of the dolines, two or more of similar or different form may unite by the intersection of their rims, and an ouvala is formed. The ouvala is a multiple doline and such forms are common in the mature karst. The altitudes of the uniting dolines are not always the same and the lower one sometimes makes a capture. In this case, as time goes on, the smaller or higher doline is left as a dale-like form on the side of the larger depression.

In the vicinity of Mammoth Cave there are "cave-in" dolines irregular in outline, asymmetrical in profile, and with a great range of size, most of them caused by the collapse of roofs of caves. Several are large enough to have received individual names, such as Hunt's Sink, Cedar Sink, Double Sink, and Deer Park. In plan, most of them are very irregular, reflecting in a general way the dendritic drainage pattern on which they have developed; those on the Cypress upland, not being influenced by narrow valleys, have a more regular form. The plan of the "cave-in" dolines is conditioned by the pre-karst valleys in which they are located. If the depression is large, there are tributary arms representing the tributary streams of the pre-karst valleys.

The diminution of the karst-making process leads ultimately to the formation of basins, another major land form of the Kentucky karst. Genetically the basin is a filled doline. It is characterized by concave slopes, extreme shallowness, and generally by greater diameter than the doline (Fig. 7). Normally the basins mark the end of the karst process, and before the soil was disturbed by cultivation they were to be found only on the outer margin of the karst area, and

[6] W. Penck, *Die Morphologische Analyse* (Stuttgart, 1924), p. 101.

possibly immediately below the Dripping Spring escarpment.[7] Today, however, there are more basins than dolines and their distribution is quite wide. For the formation of a basin, it is only necessary for the fissures draining a doline to become choked with insoluble sediment. This stoppage occurs when the fissures become filled so that they can no longer carry away the usual amount of insoluble decalcified material. Since the fissures are normally poorly developed in the Warsaw limestone, basins are the dominant forms on the lower levels of the St. Louis limestone, but any fissure will be

FIG. 7.—Shallow basin landscape in Warren County. The basin on the right is temporarily ponded. The gentle concavity of most of the slopes, which persists to the outer margins of the basins, makes the boundary of the individual basin rather sharp.

blocked and an incipient basin developed if sufficient sediment is supplied, e.g., by soil erosion.

THE INITIAL KARST LANDSCAPES

The nature of the initial karst landscapes depends on the inherited drainage pattern, for, although the karst-making processes are now dominant, the morphology is essentially pre-karst. If the allogene streams are deeply entrenched, the first karst forms may appear on the adjacent uplands before the soluble limestones have actually been exposed in the immediate vicinity. On the other hand, if the underground drainage is poor, whether on account of the great distance from a deep allogene stream or on account of the insoluble character of the limestones in the upper horizons, surface streams

[7] S. N. Dicken, "A Kentucky Solution Cuesta," *Jour. Geol.*, Vol. XLIII, p. 539.

may continue long after the Chester sandstones have been removed. Thus the character of the first karst forms depends on the type of pre-karst landscape upon which they are developed.

In general, three stages may be recognized, as follows:

Developed upon the sandstone upland
- I *a*. On smooth or gently rolling Cypress plateau
- I *b*. On deeply dissected sandstone upland

Developed below the sandstone upland
- I *c*. Entirely on limestone

Not only are the foregoing divisions significant for the first landscapes, but their effect is carried over into the pure karst phases.

LANDSCAPE I *a*

In the southwestern part of Edmonson County solution depressions are developed on a smooth type of the Cypress plateau (Fig. 8).[8] This area is small but it represents a distinct type of initial development. The ponor is the most common form, appearing with few exceptions in the beds of the creeks and their tributaries. The dolines, most of them developing from ponors, are quite irregular in plan and profile, taking partly the form of the small stream valleys in which they are developed. They have branching arms where the doline occurs at the confluence of tributaries. The inter-doline spaces are level and flat, some of them showing the beginning of doline development without the ponor phase. Some of the larger dolines contain ponors, since the doline bottoms are not yet filled with sediment to any great depth.

LANDSCAPE I *b*

East from the landscape designated as I*a*, above the larger caves in Edmonson, Hart, and Barren counties, the karst forms appear as very large, irregular, "cave-in" dolines in the deep valleys which are entrenched on the Cypress plateau. The almost perfect coincidence of these "cave-in" dolines with the caves suggests that the landscape is dependent upon the early development of large underground channels. The general level of the higher Cypress plateau remnants

[8] U.S. Geol. Surv. topographic map, Brownsville quadrangle. See also Mammoth Cave quadrangle.

is about 850 feet above sea level, while the bottoms of the deepest dolines are scarcely above 600 feet. The lower contact of the Cypress sandstone averages about 780 feet for the whole area, and the dip here is almost due north, approximately 50 feet per mile. The underlying limestone, the Ste Genevieve, is not much in evidence,

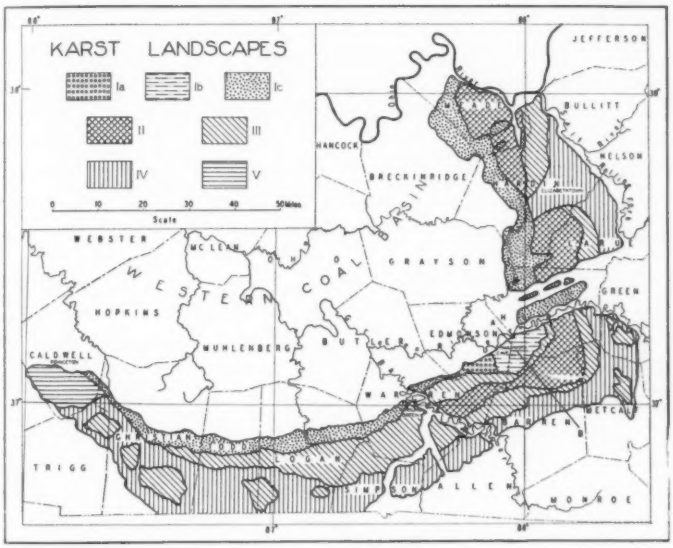


FIG. 8.—A map showing the distribution of karst landscapes. For explanation see text, except that landscape V, in a highly faulted district, is not discussed.

since its outcrop is covered with waste from the Cypress above. In general, the relief pattern is quite simple: the sandstone uplands are mostly remnant knobs, ridges, or small flats. The "cave-in" dolines are large, irregular, and with decided linear distribution. Most of them have tributary gullies; the short intermittent streams which occupy these gullies sink in the lowest parts of the dolines. The large, steeply-sloped dolines may suggest to some a rather advanced stage of karst development. But examined more closely, their irregular outline, their asymmetry of slope profile, and their relation to the normal valleys (still existing in their essential form except for

the dolines in the bottoms) indicate clearly the first appearance of the karst forms. It is suggested that the distribution of the karst forms in this landscape is determined in a very large measure by the orientation and distribution of the old normal valleys, most of which formerly flowed to the northwest. Examples of such valleys are plentiful in the vicinity; but, being without streams, not all of them have names.[9]

These dead surface valleys containing karst forms are all oriented approximately down the dip of the strata. In non-karst valleys to the north of Green River, the surface streams flow for many miles up the dip of the strata. It is evident that the deep entrenching of Green River below the plateau has played an important rôle not only in the formation of these valleys, which are now captured by karst forms, but also in the formation of the underground channels upon which the surface forms depend.

LANDSCAPE I *c*

Along the inner margin of the Barrens from the Ohio River to Bacon Creek in northern Hart County, and west of Bowling Green as far as Princeton (Fig. 8), few karst forms appear on the sandstone upland. The continuation of the Dripping Spring escarpment is highly irregular and many small streams have maintained their courses across it. Below the escarpment—that is, to the south and east—there are many karst forms in the low areas, but even here the outline of former stream valleys is very clear and their dendritic pattern is apparent. On the adjacent ridges a few small karst forms represent initial stages of development and, since intense karst erosion tends to destroy the normal stream valleys, it seems safe to assume that underground solution has not long been effective here. Viewed from a distance the landscape presents the appearance of a normal ridge and valley pattern and only on close view are the karst forms evident. In other words, the gross morphology of this landscape is pre-karst, the detailed morphology is karst.

It will be noted from Figure 8 that the three types of pre-karst landscape described above are very unequally distributed. Landscapes I *a* and I *b* are limited to comparatively small areas in the

[9] U.S. Geol. Surv. topographic map, Mammoth Cave quadrangle.

vicinity of Mammoth Cave, whereas landscape I *c* occupies a narrow but elongated region, with minor interruptions, from the Ohio River in Meade County to Princeton in Caldwell County. Apparently landscape I *c* is the normal pre-karst stage in Kentucky, and it is only on account of local intensification of the karst processes that I *a* and I *b* could develop. It remains to determine what factors contribute to the foregoing conditions. For Landscape I *b*, and to a lesser extent I *a*, the presence of a deeply entrenched allogene stream, Green River, is one of the most significant differences from landscape I *c*. The relation of Green River to the dip of the limestone strata has already been discussed above, but it is doubtful if this relation is the only contributing factor. The greater purity of the limestones and the slightly steeper dip are also important.

LANDSCAPE II: THE DOLINE KARST

The doline karst, the most typical karst landscape in Kentucky, has on the whole a rather limited extent (Fig. 8). The largest area extends from the Ohio River in Meade County to Hart County. The dolines develop largely from ponors, which do not normally originate in stream beds, for on the limestone surfaces below the Dripping Spring escarpment stream valleys are wanting. The ponors develop in the bottoms of the large basins, once the insoluble material has been removed by the underground channels. Thus a basin is not always an indication of the disappearance of karst, but is sometimes merely a phase in the development of dolines. After a heavy rain, the upper layers of the soil are saturated; and the deepest fissures normally absorb most of the water, but the deepest fissures in the basins are covered with the greatest thickness of insoluble soil and débris. Consequently the fissures on the basin margins are nearer to the surface and ponors and dolines are more likely to develop there than in the center. The development of smaller depressions in the larger basins depends on the removal of insoluble material; and the fissure which can engulf the greatest amount of this débris will develop the largest depression. But, the larger and deeper the depression, the more it is subject to filling by denudation; and after this occurs, another smaller basin is developed. Throughout the duration of the pure karst this process continues. Few or no individual forms endure

from the beginning of landscape II to its close. This form sequence gives rise to the characteristic landscape typified by the region of southern Edmonson County and northwestern Barren County.[10] Not only are dolines the dominant form, but so active are the karst-making processes in this type that the dolines appear in great diversity of form. Similar form associations are usually termed "mature" karst by those who have applied the concept of a cycle of erosion to the karst.[11] In Kentucky it is restricted in its distribution to the upper parts of the St. Louis limestone and in a few localities to the lower sections of the Ste Genevieve limestone. As has been noted before, the Ste Genevieve would probably develop a similar surface but for the presence of the Cypress sandstone in the Dripping Spring escarpment. The Upper St. Louis limestone, however, does not everywhere develop this sort of surface.

The soil of the doline karst is naturally the most important factor in rendering the bottoms of the dolines water-tight, since it is here that the clay-loam soil accumulates to the greatest depth. The surface layer of the soil is a chocolate brown clay-loam, fairly porous, and capable of absorbing considerable moisture. The medial parts of the soil profile consist of heavy red or yellow clay. Mingled with the clay, especially in the lower part of the soil profile, are a great many angular and subangular fragments of limestone which have been detached from the bedrock by solution. Some of these rock fragments show only slight evidence of solution on the surface, others have been completely penetrated by the dissolving waters and are now only porous, spongy masses known locally as "burr stones" or "barren rock." It is only upon cultivation and washing of the slope that these fragments of rock, called collectively "niggerheads," are exposed at the surface in great quantities (Fig. 6). In many sections of the Kentucky karst, and for that matter in the Blue Grass region, the farmers have collected piles of these rock fragments from the fields.

The surface of the doline karst appears as a rolling plain with the highest points lying approximately at the same level, but with the depressions having no definite level. Most of the departures from the

[10] U.S. Geol. Surv. topographic map, Mammoth Cave quadrangle.

[11] Alfred Grund, "Geographische Zyklus im Karst," *Zeitchr. d. Gesellch. f. Erdk. z. Berlin*, No. 8 (1914).

upper level are closed depressions, dolines, ouvalas, or basins, or occasionally gentle domes of irregular form between the dolines. On this type of surface the simple symmetrical doline is the exception rather than the rule. Regular dolines tend to develop only if the form is somewhat isolated. But usually two or more depressions intersect, so that the higher rims of the dolines are not continuous for the whole circumference. On the slopes of the dolines there are sometimes benches or dale-like forms which suggest that the smaller doline has been captured by the larger one. In general there is no opening in the bottom of the dolines, but all the water which falls upon their slopes finds its way underground by percolation. The dolines vary from 20 to 100 feet in diameter, and the slopes vary from 8° to 20°, in rare instances being even steeper. Most of the dolines are more than 30 feet in depth. The most reliable criterion of the doline is the convex slope, which indicates that solution has been more effective in lowering the depression than in attacking the slope. As the bottom of a doline is being deepened the slope of the sides is being increased so that there is movement down slope which tends to fill up the bottom. There is obviously a point where equilibrium between denudation and karst erosion is reached, which varies with surface and underground conditions. Another factor which prevents the development of great relief is the soil cover and the residue of insoluble débris. This cover is usually thickest in the depressions, and tends to protect the underlying rocks from solution. As the land is lowered, it is entirely normal for the drainage of some dolines to become stopped and for these dolines to become basins. The greater proportion of basins in the nothern doline karst suggests that the existence of the doline is constantly jeopardized by the small size of the underground channels. Thus, even at the height of its evolution, the doline karst is unstable.

LANDSCAPE III: THE BASIN KARST

As the forms of stage II are successively entrenched by the karst-making processes, and as their higher parts are reduced by denudation, the level of the land is finally lowered until the fissures reach the impermeable bed, or until the proportion of insoluble material greatly increases. Although no definite stratigraphic horizon may be

designated as the impermeable bed for the whole area of the Kentucky karst, in most cases it is the shaly and cherty limestones of the Warsaw formation. These establish a level below which the karst processes cannot function freely; as a consequence there is soon a distinct morphologic change on the surface. The fact that the lithologic change from the St. Louis to the Warsaw is irregular and in places rather gradual may obscure the effect of the insoluble bed, but in no sense destroys it. This impermeable bed is a definite base level for effective solution, and the most noteworthy result, so far as surface morphology is concerned, is the gradual discontinuance of karst-making while surface denudation continues—is, in fact, at first accelerated. Immediately the relief decreases, and the profiles of the depression slopes change; the fissures, no longer large enough to transport the insoluble material supplied to them by denudation, become choked with sediment. The bottoms of the dolines can no longer be deepened, protected as they are by very thick débris. As the dolines are filled with sediment their rims are reduced. The profile changes from convex to concave, and in this manner basins are formed. All the stages in the transformation of dolines to basins may be observed in the Kentucky karst. The change in slope profile begins near the center of the dolines, where sediment is being deposited. As less and less of the insoluble sediment is being carried away by the underground channels the area covered with sediment widens, extending the local base of denudation toward the rim of the dolines. Many basins reveal clearly on their peripheries, where for a short distance a convex slope still remains, that before filling with sediment the depression was a doline. If the soil on the slopes of the doline is permeable, very little material is removed by surface water. If the soil becomes impervious through long-continued cultivation and does not absorb all of the precipitation from the heavy rains, the doline becomes ponded. Many hundreds of dolines exist whose bottoms after a heavy rain are covered to a depth of one or two feet with water (Fig. 6). Ponding tends to make the bottom of the doline nearly flat. Several measurements showed that as much as 5 or 6 inches of mud were deposited in the bottom of a doline. The farmers know very well which dolines are subject to ponding, and have a fair idea as to how long the water will stand in them. Usually the do-

lines not permanently ponded will hold water only a few hours, not long enough to damage the crops planted in them.

The impermeable bed, normally the lower limit of the karst, is by no means the single cause of karst basins. Attention has already been called to the basins at the foot of the Dripping Spring escarpment, caused by the abundance of insoluble sediment furnished by the Cypress sandstone. In order for basins to be formed, it is only necessary to have a greater quantity of insoluble sediment than can be removed through the fissures. In the case of the impermeable bed the fissures become smaller and finally disappear. Near the sandstone knobs the fissures remain of the same size, but the added burden of sand is too much for them to remove. The basins formed in this manner have essentially the same characteristics as those developed on or near the impermeable bed. This landscape is a smooth, gently rolling plain, with depressions here and there which seem to be less than 3 or 4 feet below the general level of the country (Fig. 7). Here the basins are the dominant land form; many of them are large; all of them are shallow, with typical concave slopes. Their infrequency, large size, and irregular ground plan suggest that the basins have been formed by the union and filling of several dolines. The slopes are so gentle that, even where there has been intensive cultivation of corn or tobacco, field erosion is uncommon.

West of Warren County the doline karst exists only in scattered bits or not at all, owing partly to the less soluble character of the limestones and partly to the low elevation of the land with respect to the allogene streams. Basins develop independently upon those surfaces where streams have persisted until the limestone is exposed. Much water enters the underground channels and the streams become intermittent. Basins develop in these shallow stream valleys without the appearance of ponors, since the bottoms of the streams are filled with insoluble sediment. The percolation of the surface waters through this layer of insoluble sediment enlarges the fissures until they are able to carry away all the water. Usually in this case the sediment is not removed from the bottom of the basin as rapidly as denudation fills it, and thus the basin persists until the impermeable bed is reached. Although the basin is a "pure" karst form, it represents less intensive karst action than the doline. Whenever the

karst processes are retarded, the dolines tend to develop into basins. Many farmers testify that dolines on their farms have filled to a depth of 10 to 15 feet within their memory. The basin karst has the widest distribution of any of the karst types. Throughout the entire crescent of the Kentucky karst the basins occupy the outer margin of the doline karst, and there are isolated patches in Green, Metcalf, Logan, Todd, and Christian counties. The character of the basins may be seen to best advantage in the type of surface next described, the stream-basin phase. The basins, while no longer existing as closed depressions, are still parts of the newly formed stream valleys, and in favored places the entrenching of the streams has exposed sections of the basins. The character of the contact of rock and soil indicates that many basins have been formed by the merging and filling of several small dolines.

LANDSCAPE IV: STREAMS AND BASINS

If the insoluble layer, above which the basins are formed, is very thick it marks the end of the karst. The cessation of underground drainage occurs when solution practically ceases, and the passages become stopped with insoluble sediment. In Allen County this usually occurs before the impermeable bed is exposed, and the Warsaw shaly limestone can only be seen in the stream valleys which are well established to the south. In reality it is impossible to designate the exact horizon at which effective solution ceases.

As the filling of the basins continues, the sediment in the deepest part becomes so thick that water can percolate only slowly through it to the underground channels. Concurrently small rivulets appear on the margin of the basin and in times of heavy rains transport surface soil to its bottom. The ultimate result of this filling of the bottom and wasting of the rim of the basin by stream action as well as by denudation is to subdue the basin as a land form. As time goes on water is ponded in the bottom of the basin and, finding the lowest point on the rim, flows to the adjacent basin and thus the stream is formed. For some time, of course, the stream is intermittent.

At the beginning of karst-making the position of the ponors in the bottoms of the valleys was noted as the first indication of the karst

landscape. Logically, the termination of the karst forms is revealed first in the valleys, while on the ridges and knolls the karst forms persist. The valleys which develop from these basins differ in many respects from those found in areas long subject to surface drainage. In the first place the profile is determined by the relation of the basin bottoms to each other. Naturally the basins in lower elevations develop stream courses first, while the depressions in the higher part of the upland remain closed. This follows if we accept the impermeable bed as the immediate cause of the reappearance of streams. The characteristic profile of most of the smaller tributaries is as follows: The lowest part of the tributary is scarcely different from a normal valley; the middle parts of the profile show strong influence of the basins on which it is developed. There are benches where the gradient is slight and scarps where the gradient is steeper. The head of the stream is generally in a well-defined basin, which, having only one end open, is dale-like in form. The plan of these young stream valleys is also determined in part by the basins. The valley is alternately wide and narrow, wide in the center of the former basin, narrow where the stream has cut through the rim. At the narrow places, limestone appears in the bottom of the stream bed, whereas in the wider parts the stream is cutting into débris which formerly filled the basin.

The change from basins to valley does not proceed without interruptions; as the streams are entrenched they frequently encounter an underground channel which is large enough to carry all the drainage, and the stream becomes a "sinking creek." This process is exactly the same as the development of the first karst forms noted above, and represents a temporary rejuvenation of the karst.

The stream-basin landscape covers almost as large an area as all the other landscapes combined. Stretching from the Rolling Fork of Salt River around the entire outer margin of the karst almost to Princeton, the zone of streams and basins varies in width up to nearly 15 miles, though the average is about 8 miles. The total length, allowing for interruptions, is nearly 200 miles. Throughout the entire area this type of surface is developed upon the lower phases of the St. Louis limestone, and on the upper parts of the Warsaw. In

the western part, however, the upper St. Louis and even the Ste Genevieve limestone are covered with streams and basins, since the doline karst and the basin karst do not develop here. In the vicinity of Rolling Fork River the steep escarpment known as Muldraugh's Hill marks the eastern boundary. Farther south the boundary is less definite, the basins giving away gradually to a network of small streams.

STREAM FLUTING AND STREAM EROSION

JOHN H. MAXSON AND IAN CAMPBELL
California Institute of Technology, Pasadena, California

ABSTRACT

Swiftly moving sand or silt-laden water currents sometimes abrade grooves, elongated in the direction of flow, in stream boulders and in the bedrock of the stream channel. Discontinuous grooves of irregular pattern result from turbulence of the water flow. In this article the grooves are termed "flutes," and the process of their formation is called "stream fluting." The importance of stream fluting in fluvial erosion is discussed. The process is analyzed on the basis of excellent examples observed in the inner gorge of the Grand Canyon of the Colorado River.

INTRODUCTION

Under certain favorable conditions stream erosion produces interesting minor forms, "stream flutes," which have almost completely escaped the attention of American geologists. While special conditions of current velocity and content of suspended matter are necessary for the development of conspicuous flutes, the process of stream fluting is probably quite generally operative, although the results of its action may be either slight or concealed. According to the general concept of stream erosion, rock fragments are comminuted by fracturing and by abrasion and solution as they are transported downstream. In this process the stream bed is worn and the tools are rounded. The concept introduced by fluting is that turbulent flow is very important in stream erosion and that under some conditions fluting is so effective that boulders may be greatly reduced in situ and may, during this reduction, retain their angularity.

The actual method by which flutes are produced involves complicated and unsolved problems in hydrodynamics and therefore will be touched upon only in a most cursory fashion in this paper. Much more theoretical and experimental work will be required for the understanding of the factors and their manifold conditions of application in stream fluting.

The attention of the writers was first drawn to this curious phenomenon while studying the Archean section of the Grand Canyon, an investigation being sponsored by the Carnegie Institution of Washington. During this work there was frequent occasion to

traverse the deltas of streams tributary to the Colorado River. On these deltas such coarse débris has been deposited by high-gradient tributaries that the Colorado River itself has been unable to dispose of it. As a result, the river is thrown against the opposite bank and descends over the partial dam as rapids (Fig. 1).

Access was had to the mouths of Pipe Creek, Bright Angel Creek, Monument Creek, Hermit Creek, and Boucher Creek in the Kaibab

FIG. 1.—The Grand Canyon of the Colorado River, looking northwesterly from the Tonto platform west of Hermit Creek. In the lower portion of the inner gorge note the delta of Boucher Creek encroaching upon the river channel.

division of the Grand Canyon. While fluting on boulders was frequently observed and fluting on bedrock occasionally seen, the present studies have largely been made on the delta of Hermit Creek some 6 miles northwest of the village of Grand Canyon. This delta during a low-water stage of the river is shown in Figure 2. On the delta are found boulders ranging up to 15 feet in diameter. These include schists(subordinate in number) from the Archean, and from the Paleozoic section sandstones, shales (subordinate), limestones, cherty limestones, and limestone breccias. The calcareous rocks exhibit most clearly the flutes to be described. Sandstones are but

slightly susceptible to fluting, although faint flutes were found on some of the larger boulders. Schists are occasionally well fluted.

The flutes are definitely formed under water, and not by abrasion of wind-borne sand. In the region studied, strong winds were frequently encountered; but they swept *up* the main canyon and its tributaries. The flutes were observed only within the river channel itself and were always directed downstream. Moreover, as illus-

FIG. 2.—General view of the delta of Hermit Creek showing constriction in channel and rapids in the Colorado River. Note the faint high-water mark on the talus slope on the north side of the river.

trated in Figure 3, boulders in the process of fluting were observed partially submerged in turbulent water.

EARLIER OBSERVATIONS

In a short note[1] followed by a more complete discussion[2] Maurice Lugeon has called attention to what he terms "a new method of stream erosion." Inasmuch as the latter journal is not readily available to many American geologists, it seems desirable at this point

[1] "Sur un nouveau mode d'érosion fluvial," *Comptes rendus*, Vol. CLVI (1913), pp. 582–84.

[2] "Le striage du lit fluvial," *Annales de géographie*, Vols. XXIII–XXIV (1914–15), pp. 385–93.

to summarize M. Lugeon's analysis in some detail. In discussing fluviatile erosion he says:

> To date the power to cut the river channel has been attributed exclusively to descending eddies. . . . . These eddying movements clearly remain the principal method of stream erosion [in bedrock] . . . . [but] to this phenomenon . . . . must be added a new method in which the water with its suspended material acts as if the currents were horizontal, sub-horizontal, or rectilinear. There should [thus] be produced veritable sand blasts, and fluviatile erosion should be decidedly analogous to eolian erosion. The medium only is changed. Instead of being transported by air, the sand is carried by water; but the effect remains the same. . . . . These striae . . . . I discovered along the Yadkin River in North Carolina, and I took back to Europe large specimens of the engraved rock. Shown to authorities on desert action, they have not hesitated, seeing the patina on the rock, to call them good examples of eolian erosion.[3]

In the development of the phenomenon, to which he says a name[4] should be given, M. Lugeon notes two important localizing factors:

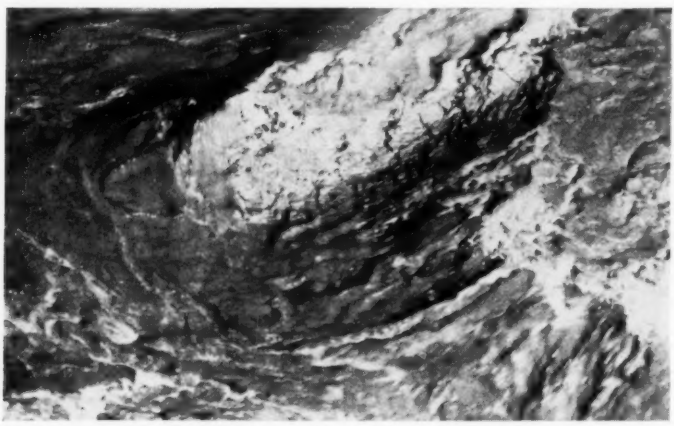


FIG. 3.—A partially submerged limestone boulder in the rapids at the delta of Hermit Creek showing some of the eddy currents on the upper surface responsible for developing pocket flutes. The current is moving from right to left, and the exposed portion of the boulder is 3 feet long.

First, the flutes are confined to a zone from $\frac{1}{2}$ to $1\frac{1}{2}$ meters above the low-water stage of the river and occur within a lateral distance of

[3] Abridged translation, with parenthetical words added by the writers.

[4] In his articles Lugeon refers to the features variously as "current striations," "fluvial engraving," "pitted cusps," "elongate furrows," "grooves," etc.

not over 10 meters from the main channel. Second, they are found only on rather hard, compact rocks. They are lacking, for example, on argillites. On the other hand, he notes that on a porphyry "the striae cut across the microlitic section of the rock as well as the phenocrysts; in other words, the scouring has no relation to the intimate rock structure." Lugeon reproduces photographs of specimens which are in all respects similar to those accompanying this article. He further figures a portion of a turbine rotor from the generating station at Zermatt (using water from a glacial torrent) which is worn into a pattern similar to stream flutes. In this connection, however, the writers have seen, in the Mechanical Engineering Laboratory of the California Institute of Technology, a turbine rotor, which used clear water in the Sierra Nevada, etched with grooves resembling flutes as a result of the little-understood process of cavitation. It will be noted in subsequent pages that the writers do not agree with M. Lugeon in ascribing flutes to horizontal or rectilinear sand blasts, but instead consider them to be developed by turbulent sand blasts.

W. H. Hobbs[5] has briefly mentioned the phenomenon, suggesting that it may be more common than generally realized; but he neither figures it nor describes it. E. D. Elston in his discussion of potholes notes that

> where strata of unequal resistance to the grinding process . . . . occur within the depth of a single hole, the interior is commonly fluted. . . . . Possibly such fluting in some cases is due to variations in the erosional effectiveness of the currents moving in the hole, due to variations in the stream velocity and its sedimentary load.[6]

Eliot Blackwelder[7] has recently mentioned the grooving effects of moving currents.

SPECIAL EROSIONAL CONDITIONS IN THE COLORADO RIVER

Before discussing the process, its results, and its significance, it will be useful to understand conditions in the river where it occurs.

[5] "The Erosional and Degradational Processes of Deserts, with Especial Reference to the Origin of Desert Depressions," *Annals Assoc. Amer. Geog.*, Vol. VII (1918), pp. 25–60.

[6] "Potholes, Their Variety, Origin, and Significance," *Sci. Monthly*, Vol. V (1917), pp. 554–67; Vol. VI (1918), pp. 357–62.

[7] "Grooving of Rock Surfaces by Sand Laden Currents," *Geol. Soc. Amer. Bull. 44* (1933), abst., p. 167.

The Colorado River in the Grand Canyon is a stream of high gradient, having a drop of about 13 feet per mile. According to the records[8] of the gauging station operated by the Water Supply Branch of the United States Geological Survey at the mouth of Bright Angel Creek (6 miles upstream from Hermit delta), in the period 1922–32 the maximum discharge in any single day was 127,000 second-feet on July 3, 1927, and the minimum discharge was 700 second-feet on December 28, 1924. The fluctuation in river level between flood and low water may be as much as 30 feet. During flood discharges of 100,000 second-feet the mean velocity in the total cross section of the river is about 10 feet per second.

The size distribution of débris carried by the Colorado River has not yet been studied in a quantitative way. Observation, however, suggests that there is a relative scarcity of fragments of intermediate size. Thus the river itself possesses a brownish color from the large amount of suspended silt and fine sand which it carries and which is presumably largely derived from tributaries upstream from the Grand Canyon. Gravel is relatively rare in bars, which are principally either sand (carried during flood periods) or boulders (derived from the Grand Canyon drainage area itself).

The maximum amount of suspended matter recorded passing the Bright Angel station was 27,600,000 tons,[9] which occurred on the single day of September 13, 1927. This huge figure includes only the silt transported in suspension in the water body. It does not include the bed load transported along or near the bottom of the channel, although this is estimated as constituting about 20 per cent of the total load of the Colorado at Yuma.[10] The size of the particles carried in suspension is greater as the bottom of the channel is approached, as is shown in the mechanical analysis of silt collected at Yuma from the Colorado River, given in Table I.[11] When this sample was taken, the river was carrying 9,000 second-feet and was cutting bars of previous high water, so that more coarse material was present than usual. However, it is probable that the average sus-

[8] *U.S. Geol. Surv. Water Supply Paper 734* (1933), p. 15.

[9] *U.S. Geol. Surv. Water Supply Paper 636* (1930), p. 32.

[10] Samuel Fortier and H. F. Blaney, "Silt in the Colorado River and Its Relation to Irrigation," *U.S. Dept. Agric. Tech. Bull. 67* (1928), pp. 52–53.

[11] *Ibid.*, p. 74.

pended matter in the Grand Canyon section of the river is considerably coarser than that at Yuma downstream. It may be readily seen from the conditions outlined above that in the Grand Canyon portion of its course the Colorado River carries bodily an ample amount of fine débris at sufficiently high velocity to be very effective in abrading the bedrock and boulders of the channel.

TABLE I

Depth	Passing 20* Retained 40 per Cent	Passing 40* Retained 60 per Cent	Passing 60* Retained 80 per Cent	Passing 80* Retained 100 per Cent	Passing 100* Retained 200 per Cent	Passing 200* per Cent
Top.....	0	2.56	4.06	32.03	55.88	5.47
Middle.....	0	3.27	20.76	51.49	20.17	4.31
Bottom.....	0	8.69	41.86	31.65	14.53	3.27

* These numbers refer to the mesh of the screen passing or retaining the given percentage of the sediment.

Solution is also an important means of erosion in the Grand Canyon drainage area. The average daily load of dissolved substances passing the Bright Angel station during 1927 of 43,240 tons, compared with 45,280 tons at Topock, about 330 miles downstream, during the same period, is indicative of the total amount of material going into solution in the intervening region, since there is but one large perennial tributary, the Virgin River of Nevada. Only a small fraction of this course of the Colorado is actually in limestone. Some of the salts in solution (sulphates, bicarbonates, and chlorides of sodium, calcium, and magnesium) must be derived from boulders of limestone and other rocks brought to the Colorado channel by intermittent tributaries. Fine particles removed from the boulders by abrasion, by reason of the large surface area which they present to the solvent, would be expected to go into solution.

TURBULENCE

The development of water current as a result of hydraulic gradient, and the correlation of varying velocities with stream load, has received considerable attention since the classic studies of G. K. Gilbert.[12] However, the significance of turbulence in transporta-

[12] "The Transportation of Débris by Running Water," *U.S. Geol. Surv. Prof. Paper 86* (1914).

tion of sediment has only recently been appreciated,[13] and the detailed action of turbulent flow in erosion of solid rock has not been discussed at all. The bedrock and boulder flutes in the Grand Canyon offer an opportunity for study of turbulence in erosional phenomena in a natural channel.

The flow of a fluid along a plane surface is considered to be laminar. The velocity of forward movement of the hypothetically independent layers decreases progressively toward the limiting surface. This relationship has recently been discussed by Th. von Karman, of the Guggenheim Aeronautics Laboratory of the California Institute of Technology, in outlining "the theory of laminar skin friction."

> In laminar flow the interaction between adjacent fluid layers consists of so-called "molecular friction"; the shearing stress, i.e., the friction per unit area, is equal to the product of the rate of shear (slope of velocity in the case of parallel flow) and the viscosity coefficient. The latter is a characteristic physical parameter of the fluid, dependent chiefly on the temperature, practically independent of the velocity. In turbulent flow an additional interaction is due to the momentum transfer from layer to layer due to velocity fluctuations.[14]

Turbulence may involve fluctuations in velocity in any direction within the fluid. It will be developed where any inequality appears in the bounding surface. However, flowing water does not develop turbulence effective in cutting below a velocity of 3 or 4 feet per second. The Colorado River near the surface may be observed to have "turbulence bodies" up to several feet in diameter. The vortices developed near the bed, as judged from flutes, must have diameters limited to a few inches.

The majority of the vortices effective in abrading the rocks of the stream bed appear to have axes roughly parallel to the confining surface and to be narrowly limited in lateral extent. The rough periodicity of the flutes on the rock surfaces must be due to rhyth-

[13] J. B. Leighly, "Toward a Theory of the Morphologic Significance of Turbulence in the Flow of Water in Streams," *Univ. Calif. Publ. in Geog.*, Vol. VI (1932), pp. 1–27; M. P. O'Brien, "Review of the Theory of Turbulent Flow and Its Relation to Sediment-Transportation," *Trans. Amer. Geophysical Union* (1933), pp. 487–91; Leighly, "Turbulence and the Transportation of Rock Débris by Streams," *Geog. Rev.*, Vol. XXIV (1934), pp. 453–64.

[14] "Turbulence and Skin Friction," *Jour. Aero. Sci.*, Vol. I (1934), pp. 1–20.

mic oscillation of velocities at present inexplicable on theoretical grounds. The diagrams shown in Figure 4 illustrate the hypothetical development of the vortices. The overlapping lip on the upstream

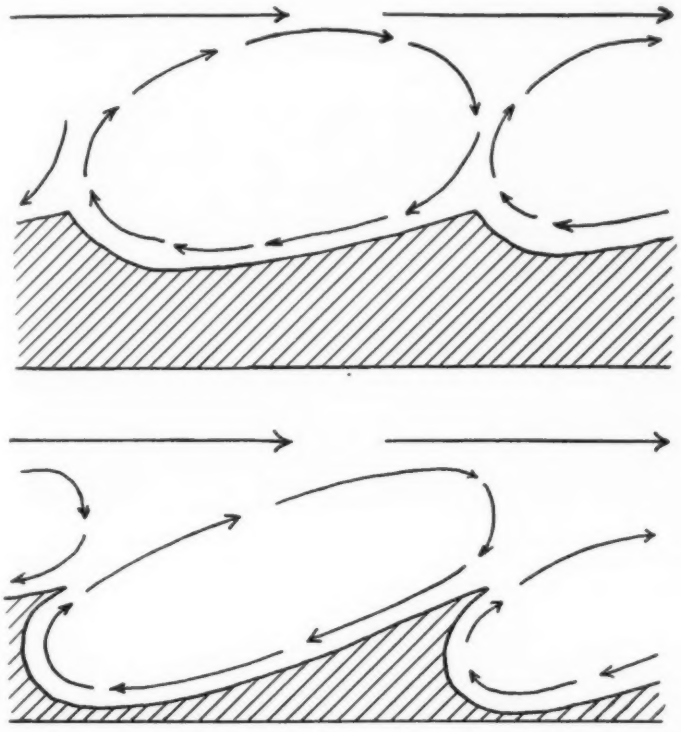


FIG. 4.—The upper diagram shows the vortices in a current moving to the right and the incipient development of pocket flutes. In an advanced stage of development, shown in the lower diagram, the upstream margin of the flute is overlapped by a lip of rock.

margin indicates a water movement along the rock surface against the direction of the main current. The ellipsoidal shape of the individual vortex which increases in eccentricity as the flute is abraded may be the result of a frictional drag effect.

STREAM FLUTING

The process of stream fluting involves essentially the differential removal of material from the rock of a stream bed or stream boulders on the bed by impact and abrasion of particles of silt and sand driven by turbulent water currents. The importance of solution as a contributing process cannot yet be evaluated.

FIG. 5.—Looking down-current at a limestone boulder 4 feet in diameter showing undulation flutes resulting from current impact and the radial distribution of pocket flutes.

The type of flute developed does not depend upon the material in which it is cut, but upon the angle which the limiting surface presents to the direction of maximum flow. The rapidity of cutting depends upon the hardness of the materials involved, upon the number and sizes of the particles in suspension, and upon current velocity.

Types of Flutes.—Sweeping currents of forward-moving sand or silt-laden water tend to develop elongated parallel grooves on bedrock surfaces parallel to the direction of flow. The "sweep flutes" are particularly well developed by currents of high velocity, such as are found in torrential mountain streams of high gradient and near the lips of waterfalls.

In the case of boulders on the stream bed, the conditions of turbulence vary from point to point. The surface of the boulder farthest upstream will normally receive the first impact of the waterborne particles. The impingement is followed by reflection of the current from the point of first contact with the concomitant development of radiating vortices. They abrade broad shallow de-

FIG. 6.—Limestone boulder with undulation flutes in lower left corner. The small pocket flutes in the upper center show deflection toward a concavity on the upper surface of the boulder as a result of current control. A watch in the upper left indicates the scale.

pressions having little or no elongation in their individual directions. The boundaries of the hollows are, however, sharply defined by low ridges resulting from the intersecting curved surfaces. These markings may be described as "undulation flutes." Figure 5 shows the upstream face of a boulder with its radial distribution of flutes. Figure 6 exhibits undulation flutes in the lower left corner passing to the upper right into pocket flutes described below.

The particles of water and silt, after impinging on the upstream face of an obstruction, first suffer loss of velocity, which is gradually regained from the momentum of particles in adjacent layers as they pass around the periphery. On the periphery vortices are developed somewhat periodically. The angular momentum of the silt particles

in the vortices being greater than that in adjacent areas, pockets should be abraded under them which would tend to enlarge. In this manner it is believed that the elongated flutes of regular orientation are formed. These seem to belong to two definite classes. The first and most important class includes what may be described as "pocket flutes." In an early stage of development the depressions are shallow.

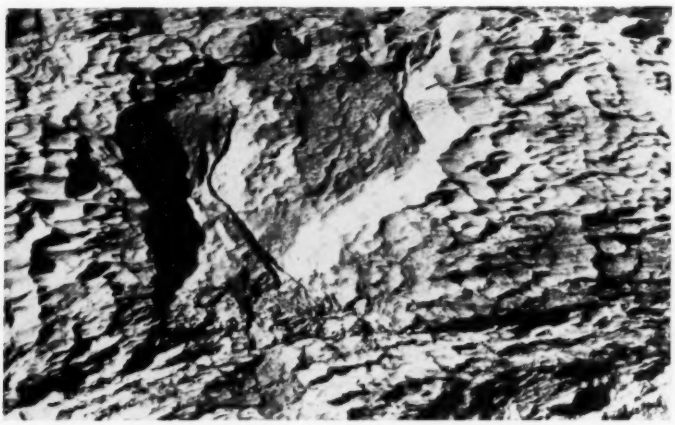


FIG. 7.—Top surface of a limestone boulder showing incipient pocket flutes on a recently exposed area. Contrast these with the well-developed flutes on the surrounding older surface.

This is shown on the top of a large boulder having well-developed flutes from which a jointed slab has been relatively recently removed. Figure 7 shows the incipient development of pocket flutes in this newly exposed area. As the flutes grow by continued abrasion, sharp ridges are formed at their intersection. These may terminate at the down-current margins in sharp apices. As the result of undercutting, the pockets are frequently overlapped on the up-current ends by sharp lips of rock. The generating vortex is illustrated in Figure 4. Pocket flutes are usually distributed over the top and sides of a boulder of irregular shape. The down-current face is unfluted unless attacked by currents deflected by adjacent obstructions (see Fig. 9). The vortices here are comparatively large and slow in motion.

Sometimes vortices with nearly vertical axes of rotation are formed in the general peripheral current and produce flutes of the second class. These usually occur where the sides of the boulder present a rather steeply sloping front to the current. As a result, more or less vertical, cylindrical grooves may be cut. In a number of cases these possess spiral ridges and have a sharp-pointed nipple in the center of the bottom surface where the abrasive action is weakened by

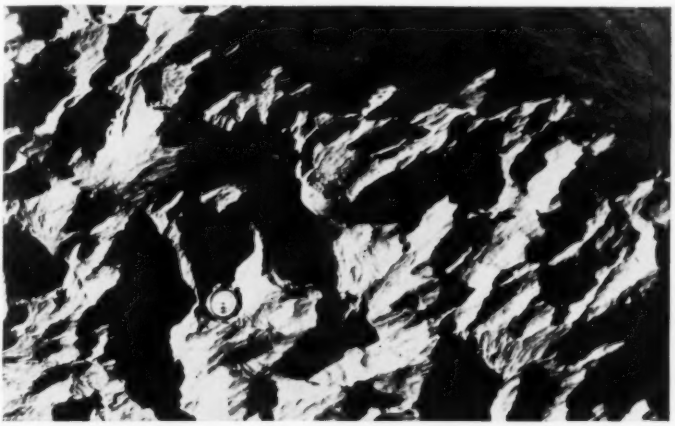


FIG. 8.—Broad pocket flutes on a limestone boulder, showing in detail the effect of minor currents in etching fret flutes.

centrifugal motion of suspended particles. These may well be termed "spiral flutes." On top surfaces and upstream faces inclined at low angle to the direction of current flow, whirlpool eddies sometimes excavate "pothole flutes."

The stream currents may in some cases have a finer pattern of vortices, producing the effect of furrowing which is superimposed on the above-described system of major flutes. These minor furrows, or "fret flutes," are illustrated in Figure 8.

Rate of fluting.—No good measure of rapidity of reduction of boulders could be obtained from these first field studies, though there is reason to believe that the process is fast rather than slow. The writers broke off fluted portions of a large limestone boulder

during the fall of 1933; and this freshly exposed area may, on subsequent inspections, give some indication of rate.

Stream fluting and eolian fluting.—Grooves abraded by wind-borne sand have frequently been observed. Examples of sand-blast

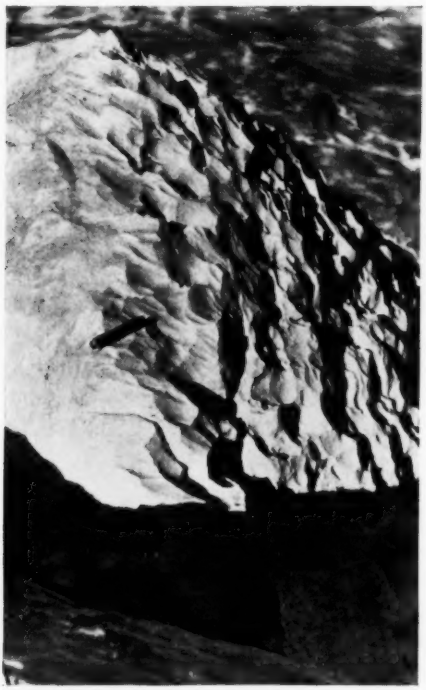


FIG. 9.—Broad pocket flutes on a limestone boulder standing at steep angle to the direction of current. Note the lack of fluting on the lee (left) side of the boulder.

action figured by Eliot Blackwelder[15] show no marked resemblance to stream flutes. Whether or not the greater gravitational control of wind-borne sand militates against large-scale turbulent abrasion is not definitely known. Turbulence in sand blasts should be further

[15] "Sandblast Action in Relation to the Glaciers of the Sierra Nevada," *Jour. Geol.*, Vol. XXXVII (1929), pp. 256–60.

investigated. Until this is done, the field evidence and association should be the most important means of distinguishing between stream and eolian fluting. In general it appears that eolian markings *usually* show a more delicate tracery—a greater control by the fine internal textures and differences in the rock in which they are carved. Stream flutes, on the other hand, are boldly carved, and pass smoothly across even considerable differences in the rock.

Geologic significance of fluting.—Stream fluting is important not only in its development of picturesque surface forms but as a concrete example of the part played by turbulent motion in corrasion. This motion renders incorrect an unqualified likening of corrasion to sand blast or filing action.

The comminution of débris in a river is due to both chemical and mechanical processes. Solution is aided by the scouring of fine particles from the rock surface. The mechanical reduction of fragments may be accomplished by abrasion of one another or of the stream bedrock and by fracturing during impacts. The chipping and rolling of rock fragments in transit downstream remain the most important methods of mechanical comminution. However, the flutes offer significant evidence of a hitherto unrecognized degree of positional stability of river boulders in a stream like the Colorado. It is obvious that in order to acquire flutes, boulders must remain quite solidly in place during the entire process of engraving. Any change of position should impose a set of flutes in a different direction, similar to the different sets of striae found on glacial boulders resulting from shift during movements of the ice. Careful search revealed no case of abnormal orientation of pattern with respect to stream direction and no case of superposition of new flutes on older ones developed in different positions. This is remarkable in view of the fact that fluted boulders range from 8 feet in diameter down to 8 inches or less.

The stability of boulders on such a vulnerable physiographic position as a tributary delta subject to frequent overflow by the master stream is further attested by the curious phenomenon of a "two-boulder" pothole shown in Figure 10. The fact that these two boulders maintained their relative position during the cutting of a pothole, partly in the one, partly in the other, is clear evidence of their stability even under flood conditions of the "mighty Colorado." It

should be emphasized too, that all these phenomena are found well within the main channel during times of high water. Because of the intermittent nature of stream action on the delta, it is believed that such a pothole could not have been formed unless the boulders maintained their exact relative positions throughout several seasons of high water.

FIG. 10.—Pothole formed on the Hermit delta between two discrete massive sandstone boulders, indicating juxtaposition over a considerable period of time.

Such a condition of stability could be expected only where the tributary is capable of transporting débris of much greater unit size than the master stream. Such a condition is found at the junction of torrential streams of steep gradient with master streams of much lower gradient. This requirement may be fulfilled in regions passing through the youthful stage of the physiographic cycle.

ACKNOWLEDGMENTS.—The writers wish to acknowledge their indebtedness to the Carnegie Institution of Washington, which, through its president, Dr. John C. Merriam, supported the study in the Grand Canyon. Thanks are extended to Professor John P. Buwalda, of the California Institute of Technology, for advice and criticism in the preparation of the manuscript.

GRANITE PEDESTAL ROCKS IN THE SOUTHERN APPALACHIAN PIEDMONT[1]

GEOFFREY W. CRICKMAY

Department of Forestry and Geological Development
Atlanta, Georgia

ABSTRACT

Pedestal rocks of granite, commonly associated with residual boulders, occur at many places in the southern Appalachian Piedmont. The rocks are essentially homogeneous in composition but exhibit marked contrasts in weathering of the cap and the shaft. They have previously been thought to have originated from joint blocks through frost action, rain wash, and decomposition. It is here shown that granular disintegration initiated by expansion through hydration is the dominant process involved. Hydration is at a maximum on the lower slopes where there is some protection from the direct rays of the sun and where evaporation is at a minimum. The pedestal rocks are restricted to peneplains of Tertiary? age.

INTRODUCTION

In the Appalachian Piedmont of the southern states, weathering has reduced the granitic rocks to an extensive mantle of incoherent clay, or saprolite,[2] that in places extends to a depth of over 100 feet. In the interstream areas there are many square miles that contain no natural exposures of granite. The outcrops that do occur are of three main types: monadnocks, such as Dunns Mountain, North Carolina, and Stone Mountain, Georgia; flat-rocks, consisting of several acres of bare flat exposure; and disintegration boulders. Associated with the "boulder outcrops,"[3] which are probably the commonest surface expression of granite, are many well-developed pedestal rocks.

A pedestal rock consists of two parts, the cap and the pedestal, or shaft, which is continuous with the underlying granite. Both parts

[1] Published by permission of the State Geologist of Georgia.

[2] Becker's term "saprolite" has been criticized because it implies putridity. "Regolith" was introduced by Merrill to include all unconsolidated surficial material and therefore embraces far more than residual weathered rock. Sederholm has proposed the name "sathrolite," derived from the Greek word σαθρός which exactly corresponds to "weathered." "Saprolite" is so firmly entrenched in the terminology of southern gold mining, however, that it is used here even though Sederholm's term is the more desirable.

[3] Surface boulders discrete from bedrock are not, of course, true outcrops but being residual they may be regarded as such for general mapping purposes.

are of identical material, but exhibit striking contrasts in manner of weathering. Even though these peculiar forms are not at all uncommon in the southern Piedmont, they have received scant notice, the only detailed account of their occurrence being a recent short paper by Julian J. Petty.[4] The purpose of the present paper is to describe pedestal rocks occurring in Georgia, supplemented by notes on those in North and South Carolina. Consideration is given their manner of origin and their physiographic significance.

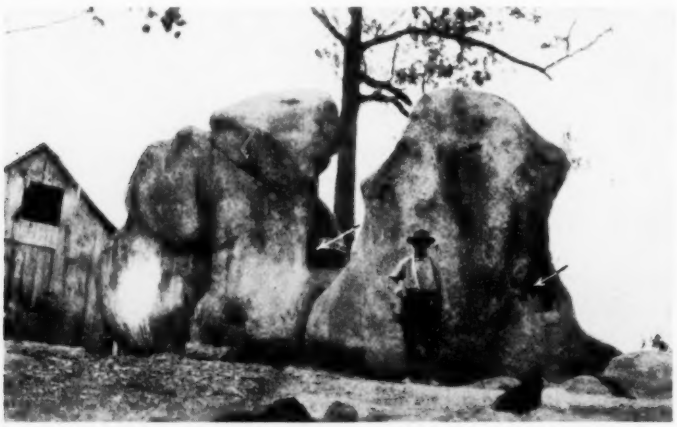


FIG. 1.—Granite boulders near Adamsville, Ga. Arrows point to cavernous openings. Note the tendency toward the pedestal form. (Photograph by S. W. McCallie.)

PEDESTAL ROCKS OF GRANITE

Near Adamsville, a suburb of Atlanta, Fulton County, Georgia, a porphyritic biotite granite is exposed in the form of residual boulders and pedestal rocks. Some of the boulders, although not true pedestal rocks because they are not continuous with the underlying granite, have assumed a pedestal form. The lower slopes are roughly etched and penetrated by holes which lead into cavernous openings inside (Fig. 1). One of these honeycombed rocks was found to be reduced to a mere skeleton near the base.

[4] Julian J. Petty, "Pedestal Rocks of Granite in the Southern Piedmont," *Jour. Elisha Mitchell Sci. Soc.*, Vol. XLVIII (1932), pp. 119–22.

A typical granite "mushroom" occurring near Adamsville is illustrated in Figure 2. The rock is approximately 12 feet in height and more or less circular in plan. The diameter of the cap is 15 feet and that of the shaft 12 feet. The cap is of hard, firm rock, sharply demarcated from the lighter-colored soft stone of the shaft, which is pitted and etched with conchoidal depressions. The base of the pedestal and of many neighboring residual boulders is surrounded by

FIG. 2.—A granite "mushroom" near Adamsville, Ga. Note the sharp demarcation between cap and shaft. (Photograph by S. W. McCallie.)

a granite sand of rusty color made up mainly of slightly decomposed feldspar and quartz.

A number of residual boulders of muscovite-biotite granite (Elberton granite) occur near Lexington, Crawford County, Georgia, which show marked differences in weathering at the base and at the top. The bases of many of these boulders are cavernous and vertically grooved, whereas the top is of smooth hard granite, fresh enough to be quarried for commercial stone. Some of the vertical grooves are crossed by thin delicate walls of granite showing that they have not been formed by rain wash. Many of the boulders are named locally in allusion to forms which they grotesquely resemble.

A "rocking stone" that can be easily moved by hand is said to occur at this locality. Residual boulders are present throughout the belt of Elberton granite, particularly in Greene County, where the granite is porphyritic. They are everywhere restricted to the flat upland of the Washington Plateau.[5]

Porphyritic granite is probably the commonest variety to assume the pedestal form. A well-formed pedestal rock, 12 feet in height,

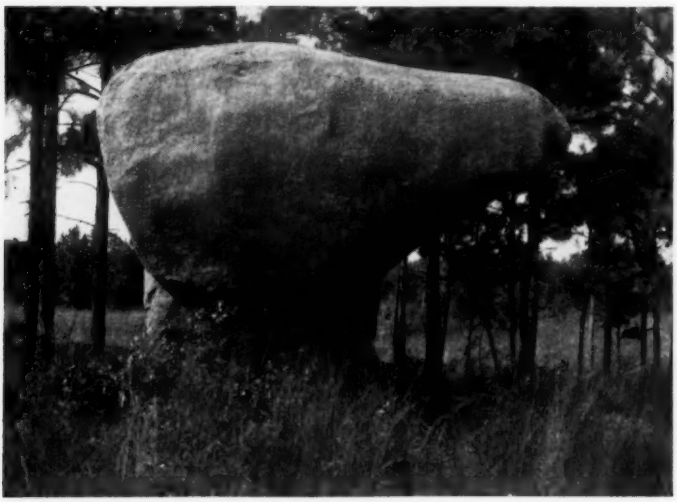


FIG. 3.—Anvil Rock near Rockton, S.C.

occurs in an area of Yorkville granite, two-thirds of a mile northwest of Filbert, South Carolina.[6] Anvil Rock (Fig. 3), on an upland, three-quarters of a mile south of Rockton, South Carolina, is also composed of slightly porphyritic granite. The cap, as reported by Petty, is of hard, firm stone in contrast to the friable character of the pedestal. Petty's suggestion that this difference is due to the painting of advertisements on the upper surface of the cap is hardly com-

[5] Laurence LaForge, "Physical Geography of Georgia—The Central Upland," *Ga. Geol. Surv. Bull. 42* (1925), pp. 55–92.

[6] A. Keith and D. B. Sterrett, "Gaffney–Kings Mountain Folio," *U.S. Geol. Surv. Folio 222* (1931), fig. 9; J. J. Petty, *op. cit.*, p. 120 and fig. 3.

patible with the great length of time involved in the development of the rock forms. Pedestal rocks of porphyritic granite near Heath Springs, South Carolina, and Concord, North Carolina, are mentioned by Petty. Boulder "outcrops" of Pinckneyville granite occur $2\frac{1}{2}$ miles northeast of Pinckneyville, Alabama,[7] but no true pedestal rocks are known in that state.[8]

The caps of many of the boulders are formed of concentric exfoliation shells truncated below. A pedestal rock of equi-granular biotite

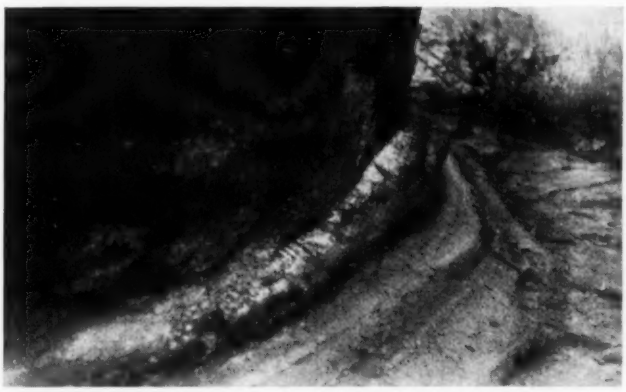


FIG. 4.—Surface trace of exfoliation shells at the base of a granite pedestal rock near Gray, Ga. (Photograph by Leon Smith.)

granite near Gray, Jones County, Georgia, shows the extension of these shells at the base of the shaft (Fig. 4). This rock, like all the others previously described, occurs on an upland surface in an area of deep saprolite.

PEDESTAL ROCKS OF GRANITE GNEISS

A well-formed pedestal rock of fine-grained granite augen gneiss occurs 3 miles north of Franklin, Heard County, Georgia (Fig. 5). The rock is about 8 feet in height, having the form of an inverted pyramid. The short shaft is made of crumbly rotten stone, the grains

[7] W. F. Prouty, "Geology and Mineral Resources of Clay County," *Ala. Geol. Surv., County Rept. 1* (1923), pl. 3 A.

[8] Stewart J. Lloyd, Alabama Geological Survey, personal communication.

of which may easily be detached by rubbing with the hand. The surrounding granite is everywhere weathered to a stiff reddish-brown clay that extends to a depth of 10 to 30 feet.

Professor Count Gibson has called my attention to a pedestal rock of banded granite gneiss that lies 100 yards south of the Atlanta-Covington highway, 2 miles west of Almon, Georgia (Fig. 6). The shaft is $5\frac{1}{2}$ feet in height, more than half the total height of the rock.

FIG. 5.—Pedestal rock of granite augen gneiss near Franklin, Ga. Saprolite in foreground is soft white clay containing streaks of thoroughly decomposed pegmatite.

It is etched in cavernous pits, mainly elongate vertically, some of which are more than a foot deep. The triangular-shaped cap has a smooth surface, in part covered with a dark-colored growth of lichen. It is made up of exfoliation shells which are truncated at the top of the pedestal. The dimensions of the cap are 12 feet in a N–S direction and 9 feet E–W. The upper surface of the cap slopes southeast. The foliation of the gneiss, which strikes N 20° W, conforms to the elongation of the cap, but seems to exert little control over the de-

tails of weathering of the shaft. Several large boulders resting on the ground on the west side of the rock are probably the remains of an adjoining pedestal rock. On a flat-topped hill south of Conyers is a pedestal rock only 2 feet high of the same granite. Sand from the base of this rock, on microscopic examination, proved to be largely quartz and kaolinic feldspar stained by iron oxides.

Boulder "outcrops" of granite gneiss occur on an upland surface near Rockford, Coosa County, Alabama.[9] Crude pedestal rocks and

FIG. 6.—Pedestal rock of granite gneiss near Almon, Ga. (Photograph by Count Gibson.)

many residual boulders are to be found near Dunns Mountain, southeast of Salisbury, North Carolina, where slightly gneissic granite is extensively quarried. Etched surfaces and other sculptural details that characterize most of the pedestal rocks were not observed at this locality.

SUMMARY OF FIELD RELATIONS

The pedestal rocks of the southern Appalachian Piedmont are composed of equi-granular granite, porphyritic granite, granite gneiss, and granite augen gneiss, of which the porphyritic varieties are the commonest. They range from 2 feet to more than 12 feet in

[9] W. B. Phillips, "The Lower Gold Belt of Alabama," *Ala. Geol. Surv. Bull.* 3 (1892), p. 86, pls. 2, 3, 4.

height. The cap is commonly of hard, fresh stone with a smooth surface, in places covered with lichen. The pedestal is generally of soft crumbly stone, etched by pits and cavernous openings. Granite sand consisting of slightly weathered feldspar and quartz, is commonly present at the base and has presumably been derived from the disintegration of the pedestal. The cap and pedestal are surficially separated by a sharp line of demarcation, owing in some cases to a break in the exfoliation shells of the cap. All the pedestal rocks and most of the boulder outcrops occur on or close to uplands which have been interpreted as old erosion surfaces. Except where associated with flat-rock exposures, the pedestal rocks are surrounded by a deep saprolite.

ORIGIN OF PEDESTAL ROCKS

The disintegration boulders which are such a common surface expression of granite in the southern states early attracted the attention of geologists. In 1841 J. T. Hodge[10] cited the widespread occurrence of the boulders as evidence of former glaciation. The boulders, of course, are not erratics but are truly residual. LeConte[11] believed that they "have resisted because harder than" the surrounding granite. According to Merrill,[12] they are essentially joint blocks, modified by decomposition which has been more rapid on the lower portions "due to the fact that this portion of the rock is kept in a state of continual moisture." Watson[13] subscribed to Merrill's theory that the boulders are simply joint blocks modified by weathering. He says: "This form of weathering has resulted from the more rapid decay on the edges and corners than on the flat sides of the jointed granite blocks, the blocks being gradually rounded and formed into boulder rock masses of varying sizes." This theory, however, fails to account satisfactorily for the pedestal rocks. The south face of the shaft of Anvil Rock is a slightly modified joint with small re-entrants at the base; the large boulders and crude pedestal rocks at Dunns Mountain are little more than weathered joint

[10] J. T. Hodge, "Observations on the Secondary and Tertiary Formations of the Southern Atlantic States," *Amer. Jour. Sci.*, Vol. XLI (1841), pp. 182–83.

[11] Joseph LeConte, *A Compend of Geology* (New York, 1898), p. 14.

[12] G. P. Merrill, *Rocks, Rock Weathering, and Soils* (New York, 1906).

[13] T. L. Watson, "Granites and Gneisses of Georgia," *Ga. Geol. Surv. Bull. 9* (1902), pp. 282–348.

blocks; but in most cases jointing has played little or no part in determining the form of the pedestal rocks.

The pedestal rocks and disintegration boulders in York County, South Carolina, according to Keith and Sterrett,[14] "appear to be confined to the purer, coarse porphyritic granite and are due chiefly to disintegration by frost." J. J. Petty,[15] in a more general discussion of the pedestal rocks of South Carolina, concludes that they are "due largely to chemical weathering which acts at or near the soil surface on projecting rock masses. Frost action, granular disintegration, and rainwash may be auxiliary agents, but their activity is made possible or more effective by weakening of the rock through chemical decomposition."

Because the pedestal rocks occur in areas where freezing weather prevails only a short time in the year, and because etching is restricted to their lower protected slopes, I believe frost action to be a relatively unimportant factor. Rain-wash is likewise negligible for, although vertical channels and grooves are present, they are commonly crossed by delicate partitions and pitted with re-entrants comparable to solution channels in certain limestones. If frost action were an effective agent it would certainly break down these thin walls before the more massive part of the pedestal. Rain-wash is sufficient only to carry away grains that have been loosened by another process, namely, granular disintegration brought about by expansion through hydration.

For the development of pedestal rocks in the arid and semi-arid regions of the western United States, where they are more abundant than elsewhere, the importance of granular disintegration has been emphasized by Kirk Bryan,[16] Leonard,[17] and Anderson.[18] Granular disintegration is determined primarily by increase of volume through hydration. Merrill[19] concluded that the degeneration of fresh granite into arable soil in the District of Columbia resulted in an increase

[14] *Op. cit.* [15] *Op. cit.*

[16] Kirk Bryan, "Pedestal Rocks in the Arid Southwest," *U.S. Geol. Surv. Bull. 760* (1925), pp. 1–11.

[17] R. J. Leonard, "Pedestal Rocks Resulting from Disintegration," *Jour. Geol.*, Vol. XXXV (1927), pp. 469–74.

[18] Alfred L. Anderson, "Geology and Mineral Resources of Eastern Cassia County, Idaho," *Idaho Bur. Mines and Geol. Bull. 14* (1931), pp. 18–19, 56–60.

[19] Quoted by T. L. Watson, *op. cit.*, p. 293.

of bulk amounting to 88 per cent. "The newly formed soil differs from the massive rock mainly in that its feldspathic and other silicate constituents have undergone a certain amount of hydration." A thorough study of the Georgia granites led Watson[20] to the conclusion that the first phase of weathering is the disruption of grains to granitic sand by hydration accompanied by only slight chemical change. Disintegration is, then, controlled by the moisture content of the rock.

The abundance of moisture near the ground surface is well demonstrated by its destructive action in promoting decay at the base of telegraph poles and fence posts, but it can hardly be called on to explain disintegration of granite 10 feet or more above the ground. Rain, particularly summer rain, appears to supply most of the moisture through which hydration is accomplished. Kirk Bryan[21] found that the development of certain pedestal rocks in the Southwest was dependent on rain, which formed a "drip curtain" from the cap and an inner film of water on the shaft. In the southern Atlantic states, where rainfall is comparatively high,[22] a summer shower drenches the entire pedestal rock, but evaporation soon dries off the upper surface of the cap. The result is that hydration with consequent disintegration is largely restricted to the overhanging, shaded portion of the pedestal. Because of the altitude of the sun, the north side would in general be more shaded than the south side, and thus one might expect the former to exhibit more overhang and more etching. This is true of a number of pedestal rocks (Figs. 1, 3, and 5, all of which are taken looking west).

Figure 7 is a photograph of a pine stump which illustrates the remarkable differences that occur on surfaces exposed to or protected from evaporation. Such decomposed pine stumps are very common in the forests of the southern states. The upper part of the stump is kept dry by evaporation and is made of firm wood. The lower part, originally protected by a bark, has been entirely decomposed (except for a central axis protected by a filling of gum) by the action of fungi whose growth was promoted by moisture. Although the decay of

[20] *Ibid.* [21] Kirk Bryan, *op. cit.*

[22] The average annual precipitation, according to the records of the U.S. Weather Bureau, ranges from 40 inches at Asheville, N.C., to 83 inches at Highlands, N.C.

wood[23] is not closely comparable to the disintegration of granite, both are determined to a large extent by moisture content. The stump illustrates the development of the pedestal form under the

FIG. 7.—Pine stump near Warm Springs, Ga. *A*, hard, firm wood; *B*, central gum-protected core. Compare form to that of pedestal rocks.

same control as granite pedestal rocks but in a comparatively brief time.

Exfoliation plays an important part in determining the form of the cap of many pedestal rocks. The origin of exfoliation shells in the granites of the southern states is not altogether certain. The occurrence of joint blocks with exfoliation shells in saprolite as much as

[23] R. H. Colley, "The Telephone Pole and the Mushroom," *Sci. Monthly*, Vol. XXXVIII (1934), pp. 378–83.

30 feet below the ground surface stands in contradiction to statements that exfoliation originates through temperature changes, causing unequal expansion of minerals.[24] It seems probable that exfoliation is to a large extent controlled by the penetration of moisture. In some cases the layering is horizontal, parallel to the ground

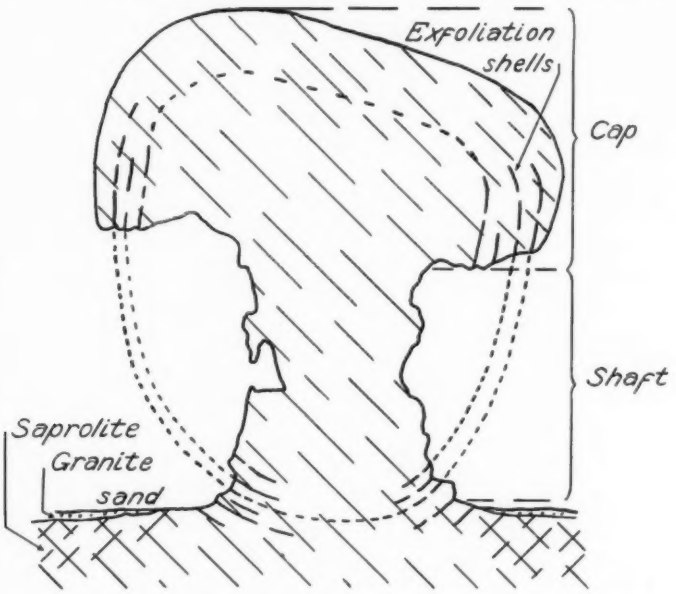


FIG. 8.—Ideal section of a granite pedestal rock, showing relation of exfoliation shells. Compare with Figures 2 and 4.

surface, and so strongly developed that it takes on much the appearance of gneissic banding. The sharp demarcation of cap and pedestal is commonly determined by the truncation of exfoliation shells as shown in Figure 8. The instability of vertical shells that formerly encased the pedestal is apparent.

Petty[25] has noted that the cap of some pedestal rocks in South

[24] Eliot Blackwelder, "Exfoliation as a Phase of Rock Weathering," *Jour. Geol.*, Vol. XXXIII (1925), pp. 793–806.

[25] *Op. cit.*, p. 122.

Carolina is protected by an iron-stained crust. The deposition of this iron oxide, called "case-hardening" by Anderson,[26] has resulted in the development of a weird and remarkable series of forms in the "Cassia City of Rocks," Cassia County, Idaho. In most of the rocks of the southern Piedmont "case-hardening" is a relatively unimportant factor in the preservation of the cap, probably owing to the fact that most of the southern granites contain less than 1.75 per cent iron oxides.

Although it is true that the pedestal rocks are found only on uplands, they most commonly occur near areas of more recent dissection. Many rest on ground slightly below the level of the upland. It is possible that the tops of such rocks represent the level of the adjoining erosion surface. Most of these old surfaces are undulating and close correlations of altitudes cannot be made.

The ultimate origin of the granite blocks from which the pedestal forms developed is not, it seems to me, an important question. They may have been joint blocks or simply knobs on former flat rock exposures. It is apparent that any irregularity that projected above the ground possessed a far better chance to survive disintegration and decomposition to saprolite than adjoining rock that did not have the advantages of drainage.

PHYSIOGRAPHIC SIGNIFICANCE

There is little evidence on the age of the pedestal rocks here described. Their restriction to uplands, interpreted as old erosion surfaces (probably of Tertiary age), has previously been noted. Apparently granite more recently uncovered in valleys has not been exposed long enough to develop either a pitted and grooved surface or the pedestal form. In this connection it is interesting to note that the "weather pits" in granite in Yosemite Valley are thought by Matthes to develop at an extremely slow rate for "not a single one is to be found within the area that was covered by the [last Pleistocene glaciation]."[27] Although climatic conditions in the two regions are somewhat different, the "weather pits" are quite similar to depres-

[26] *Op. cit.*, p. 57.

[27] François E. Matthes, "Geologic History of the Yosemite Valley," *U.S. Geol. Surv. Prof. Paper 160* (1930), p. 64.

sions and grooves on pedestal rocks in the southeast. As a working hypothesis, I suggest that the occurrence of pedestal rocks and related disintegration boulders containing "weather pits" resting on an upland of the Appalachian Piedmont may be regarded as indicating an old erosion surface. Whether the relative ages of erosion surfaces can be determined by the relative development of these residual forms is uncertain.

GEOLOGIC DEDUCTIONS FROM EARTHQUAKES OF DEEP FOCUS

J. S. DE LURY
University of Manitoba

ABSTRACT

From the maze of geophysical data little concrete evidence emerges to permit widely acceptable views on the strength of rocks at different depths in the earth's interior. Seismologists have established the existence of a high degree of rigidity down to great depths, but the commonly held view that earthquakes are of shallow origin has lent support to the opinion that correspondingly shallow rocks alone can permit the slow accumulation of elastic stresses. This opinion must change with the growing evidence that earthquakes probably originate in all levels down to depths of 700 or more kilometers. The same evidence is disturbing to the assumptions of isostasy and to those hypotheses which rest on the concept of a shell of weakness.

Attempts to explain the causes of earth-movements commonly begin with deductions from phenomena and structures which are regarded as effects of the movements. The relative success of competing hypotheses is measured by their ability to explain effects and to meet the limitations which are placed by geophysical evidence regarding the nature of the earth's interior. It might properly be inferred from the diversity of tectonic hypotheses that geophysical data offer few restraints to speculation. Nearly all hypotheses, however, submit to one limitation, that imposed by an acceptance of the principle of isostasy, and with it, the assumption of a continuous shell of weakness beneath a strong crust.

Seismology has exercised a profound influence on speculations regarding the nature of the interior of the earth. The speed of transit of seismic vibrations through all parts of the earth has established the existence of great rigidity in all levels, except possibly in a remote and central core. The earth's reaction to tides and to other outside forces indicates not only a rigidity of the same high order for the earth as a whole, but also great viscosity. Isostasy, however, seems to require that a continuous shell, beneath an admittedly strong crust, must be weak enough to permit a delicate balance in the crust. To reconcile all lines of evidence, it became necessary to assume that rocks in the shell where isostatic adjustments are effect-

ed, notwithstanding their great rigidity, must be nearly devoid of strength when opposed to small stresses of long duration. But the work of Adams and his associates indicates that, other things being equal, rock increases vastly in strength under confining pressures which are known to increase with depth.[1] The only important factor which could be summoned to offset the effect of pressure on strength is heat. Therefore, to permit the existence of a continuous shell with high rigidity and little permanent strength, it had to be assumed that a rather delicate adjustment between temperature and pressure persists throughout the shell of weakness. Not only must conditions be close to those required for fusion, but temperatures must be uniform throughout each level in the shell. Herein probably lies the explanation of the common assumption embodied in many hypotheses, that isotherms are smoothly concentric outward from the earth's interior into surprisingly shallow levels. The writer already has shown that geothermal evidence points very definitely to the conclusions that isothermal surfaces are irregular down to depths of several hundred miles and that thermal conditions decree inequality of strength in any level and a general increase of strength with depth.[2] The purpose of the present paper is to examine in a general way the bearing of the evidence of deep-focus earthquakes on the question of strength in different levels in the earth.

EARTHQUAKES OF DEEP FOCUS

Although the phenomenon of deep-focus earthquakes has long been suspected, it is only in the past few years that methods of estimating depth of origin have been perfected and a sufficient number of reliable records established to permit geologic applications.

As late as 1933, Daly, in listing the evidences in support of the concept of a weak shell, gave what might be regarded as the prevalent view of holders of that conception concerning the levels in which earthquakes originate:

> A fourth evidence is the general, though probably not absolute, restriction of earthquake foci to depths less than 50 kilometers, below which it is doubtful that considerable elastic stress can be accumulated. Much deeper foci of rela-

[1] F. D. Adams and J. A. Bancroft, "Internal Friction in Rocks," *Jour. Geol.*, Vol. XXV (1917), pp. 634–35.

[2] J. S. DeLury, "The Strength of the Earth," *Jour. Geol.*, Vol. XLI (1933), pp. 748–56; "The Magmatic Wedge," *Amer. Jour. Sci.*, Vol. XXVIII (1934), pp. 341–52.

tively weak earthquakes may be expected if the earth has been distorted (as by glacial loading and unloading) at a time so recent that the elastic strain of the deeper shells has not yet had time to disappear. However, seismologists are impressed with the comparative shallowness of most of the determined foci. For example, Jeffreys concludes that the foci of great shocks seem to lie no deeper than 35 kilometers below the surface, and that notable strength is restricted to a shell of the order of 35 kilometers in thickness.[3]

Although these views are of comparatively recent date, neither authority could continue holding them in the light of the evidence of deep-focus earthquakes which has accumulated during the past few years.

No desirable purpose would be served, even if the writer were competent, in attempting to outline and weigh the various methods which have been used to determine the focal depth of earthquakes. Methods are ably discussed by Stechschulte and Scrase, whose papers contain important references to other workers.[4] The direct concern of the geologist is with the statistical data of deep-focus earthquakes, which are already available from the findings of seismologists. Table I is compiled from comparatively limited sources,[5] but it serves all the more from its limitations to indicate that foci occur at great depths and in a wide variety of depths.

GEOLOGIC IMPLICATIONS OF DEEP FOCUS EARTHQUAKES

The evidence that earthquakes may originate at a depth of 700 kilometers and the probability that their foci will be established in all levels down to that depth will place stricter limitations upon hypotheses of earth-movements than do any other geophysical data. It is reasonably certain that at least the deeper earthquakes are caused by an elastic rebound in rocks which slip because their strength has been overcome by slowly accumulated elastic stress. It is probably true that greater stress is needed to cause slipping at

[3] R. A. Daly, *Igneous Rocks and the Depths of the Earth* (1933), pp. 197–98 (with reference).

[4] V. C. Stechschulte, S.J., "The Japanese Earthquake of March 29, 1928, and the Problem of Depth of Focus," *Seis. Soc. Amer. Bull. 22* (1932), pp. 81–137; F. J. Scrase, "The Characteristics of a Deep Focus Earthquake," *Phil. Trans. Roy. Soc.*, ser. A, Vol. CCXXXI (1933), pp. 207–34.

[5] G. J. Brunner, S.J., "The Earthquake of September 6, 1933, and Its Bearing on the Problem of the Deep Earthquake," *Trans. Amer. Geophys. Union* (1934), pp. 72–77; "Earthquake of June 29, 1934," *Prelim. Bull. Central Station, Jesuit Seis. Assoc.* (March, 1935); *Jesuit Seis. Assoc. Bulls.* (1934–35).

great depth than in shallow levels, so that greater strength in rocks is needed to permit earthquakes of deep focus. In the quotation from Daly in the earlier part of this paper, it is clearly implied that if strong earthquakes originate in any level, considerable elastic stress can accumulate in that level, and, therefore, strength comparable to, and probably greater than that of the crust must exist there. Shal-

TABLE I

RANGE OF FOCAL DEPTHS OF EARTHQUAKES IN RECENT YEARS

Approximate Depth in Kilometers	Date	Authority
50	Nov. 5, 1934	Jesuit Seismol. Assoc.
65	July 18, 1934	Jesuit Seismol. Assoc.
75	Feb. 25, 1935	Jesuit Seismol. Assoc.
100	Dec. 23, 1934	Jesuit Seismol. Assoc.
100	Dec. 24, 1934	Jesuit Seismol. Assoc.
100	Feb. 13, 1935	Jesuit Seismol. Assoc.
100	Feb. 20, 1935	Jesuit Seismol. Assoc.
100	Mar. 17, 1935	Jesuit Seismol. Assoc.
200	Dec. 4, 1934	Jesuit Seismol. Assoc.
200	Feb. 28, 1935	Jesuit Seismol. Assoc.
200	Since 1918	Scrase
300	Since 1918	Scrase
360	Feb. 20, 1931	Scrase
410	Mar. 29, 1928	Stechschulte
570	May 26, 1932	Brunner
637	Sept. 6, 1933	Brunner
700	June 29, 1934	Brunner

low earthquakes are the most destructive but there is evidence to show that deep-focus earthquakes may be stronger than the more destructive kind with shallow origin. For example, Scrase wrote of the 1931 earthquake near the Sea of Japan:

> Wadati mentions that the shock of February 20, 1931, was felt in many parts of Japan and as far away as 1,300 kilometers from the epicenter. On the other hand, the disastrous Tokyo earthquake of September, 1923, which was very much more violent, was not perceived at all at distances greater than 800 kilometers. This difference is, of course, in accordance with the idea that the shock of February, 1931, was of considerably deeper focus than the Tokyo earthquake.[6]

Seismologists were early in grasping the geologic significance of deep-focus earthquakes. After indicating the evidence of deep foci, Macelwane stated:

[6] *Op. cit.*, p. 210 (with reference).

What would be the mechanism of displacement at these greater depths remains an open question since fractures seem very improbable.[7]

Stechschulte went further:

The occurrence of earthquake-shocks at depths of three, or four or even five hundred kilometers may, I think, be taken as well established, though the processes by which such shocks originate is [*sic*] not at all clear. It would also seem that the occurrence of such deep-seated shocks must be taken into account in our study of the character of the Earth's interior, as perhaps also in such problems as the depth of isostatic compensation and the like.[8]

The most obvious conclusion from deep-focus earthquakes is that strength in general increases with depth. It is inconceivable, therefore, that a continuous shell of weakness can exist, if the remote central core is excluded from consideration. What explanation can be offered of the mechanism of deep seismic disturbances? Tides and other external forces produce only minor distortional effects and apparently they have no accumulative effect. Changes of load at the surface, brought about by gradation processes and by the accumulation and melting of ice sheets, might conceivably lead to deep disturbances, but are more likely to produce deformations within the elastic limit. It is not easy to imagine violent repercussions at depths of 700 kilometers from the melting of an ice sheet. Deep-seated earthquakes call for mighty stresses, and in the dilemma, it seems necessary to appeal to the greatest source of energy in the earth, namely, heat.

If geo-isotherms were smoothly concentric outward to a depth of 100 kilometers from the surface, the deepest earthquakes could only be explained by the collapse of an outer shell, 700 or so kilometers thick, to accommodate itself to a core which is suffering thermal contraction. Such collapses would likely be sudden, catastrophic, and infrequent. But deep-focus earthquakes are neither infrequent nor catastrophic. The wide range in radial distribution of deep disturbances, and their apparent localization in horizontal distribution, suggest differential thermal expansion and contraction, as between wide columns of an outer shell extending down 700 kilometers or more.

[7] J. B. Macelwane, S.J., "Our Present Knowledge Concerning the Interior of the Earth," *Seis. Soc. Amer. Bull. 21* (1931), p. 244.

[8] V. C. Stechschulte, S.J., *Trans. Amer. Geophys. Union 14th Ann. Meeting* (1933), pp. 311–12.

The greatest focal depth of an earthquake, so far recorded, is 700 kilometers. Jeffreys[9] estimated that cooling has disturbed the "initial thermal gradient" down to about the same depth. Such a similarity in depth is expected, if deep earthquakes are caused by stresses from differential thermal activities and we assume that the earth has solidified from a former molten state. It is highly probable that earthquakes with deeper foci than 700 kilometers will be found, and that the initial thermal gradient has been disturbed to greater depths. It is possible that in the future a statistical study of deep-seated earthquakes will throw more light upon this problem.

A rational hypothesis for the mechanism of earthquakes of deep origin seems to be permitted by the evidence: If an initial thermal gradient has been disturbed to depths greater than 700 kilometers, rocks above those depths should in general have temperatures sufficiently remote from fusion conditions for the confining pressure to give them great strength. It might be asked, however, if this general condition excludes the possibility of a continuous shell of weakness in shallower levels. In answer it can be said that geothermal evidence is opposed to the existence of a shell of weakness and favors the view that the outer earth is being continually distorted by thermal activities.[10] The evidence that earthquake foci are found at many levels down to depths of 700 kilometers, gives definite confirmation of this view. Expansion and contraction, brought about by differential generation and conduction of heat, in rocks of great strength, seem to be the most promising source for the great stresses required by deep-seated earthquakes.

The conclusions of this paper are directly opposed to hypotheses which are built on the assumption of a continuous shell of weakness, and are equally opposed to the assumptions of isostasy. There is abundant evidence in favor of the general conception of isostasy, but overwhelming evidence against the assumptions upon which the conception has grown. In this dilemma, a re-reading of T. C. Chamberlin's views will be well worth while.[11]

[9] H. Jeffreys, *The Earth* (1929), p. 154.

[10] J. S. DeLury, *op. cit.*

[11] T. C. Chamberlin, "Intrageology-Elastasy *vs.* Isostasy" (Editorial) *Jour. Geol.*, Vol. XXXV (1927), pp. 89–94.

GROWTH STAGES OF *ALLAGECRINUS AMERICANUS* ROWLEY

RAYMOND E. PECK
University of Missouri

ABSTRACT

A study of about three hundred well-preserved calyces of *Allagecrinus americanus* Rowley has shown an unusually complete series of growth stages. The arm facets develop first on the *LAR* and *RPR*, then on the *LPR* and *RAR*, and finally on the *AR*. The anal series is introduced about the same time as the facet on the *AR*. The orderly appearance of arm facets is accompanied by an increase in the size of the calyx, a lessening in the strength of the ornamentation, and a greater differentiation of the radial plates.

Immature crinoid calyces are rare as fossils, and it is very unusual to find a fairly complete series of growth stages. Exceptions to this are found among the Paleozoic microcrinoids, especially among the Allagecrinidae. These minute forms are collected most successfully from very thin shale partings in limestone, and at some localities hundreds of individuals may be taken from comparatively small samples of shale. As the shale samples ordinarily represent an area of but a few square inches it is to be expected that even a large number of individuals may represent only one species. This gives an excellent opportunity for the study of ontogenetic stages.

Wright,[1] working with Scottish representatives of the Allagecrinidae, has established several recognizable stages in the development of *Allagecrinus austinii* Carpenter and Etheridge and other related species. He concludes that, for the most part, the development of arms follows no orderly succession.

Weller[2] has recently studied and redefined *Allagecrinus americanus* Rowley, the only recorded American species of the genus. In his description he implied that some of the smaller individuals in which no anal plate could be detected might represent immature forms.

In order to obtain material for comparison with microcrinoids of

[1] J. Wright, "Scottish Species of *Allagecrinus*," *Geol. Mag.*, Vol. LXIX (1932), pp. 337–66. See also J. Wright, "Two New Crinoids from the Scottish Carboniferous Limestones, with Notes on the *Allagecrinidae*," *ibid.*, Vol. LXX (1933), pp. 201–8.

[2] J. Marvin Weller, "A Group of Larviform Crinoids from Lower Pennsylvanian Strata of the Eastern Interior Basin," *Ill. Geol. Surv. Rept. Investigations 21* (1930).

the Fern Glen and Chouteau (Kinderhookian) formations I visited the type locality of *Allagecrinus americanus* Rowley. The late Professor R. R. Rowley was kind enough to accompany me and point out the exact locality and horizon from which he obtained the type material. Two small samples collected there yielded over 300 well-preserved crinoid calyces. These calyces vary greatly in size, in relative proportions of the plates, and in the number of arm facets. At first I was inclined to recognize at least two distinct species and possibly two genera; but further comparison and study showed that they illustrated a remarkable series of growth-stages.

Allagecrinus americanus ROWLEY

1895. *Allagecrinus americanus* Rowley, *Amer. Geol.*, Vol. XVI, p. 219, Figs. 3–10.

1908. *Allagecrinus americanus* Rowley, *Mo. Bur. Geol.*, Ser. II, Vol. VIII, p. 67, Pl. 16, Figs. 39–41.

1930. *Hybochilocrinus americanus*, J. Weller, *Ill. Geol. Surv., Rept. Investigations 21*, pp. 12–15, Pl. 1, Figs. *1a*, *1b*, *1c*.

1933. *Allagecrinus americanus*, J. Wright, *Geol. Mag.*, Vol. LXX, p. 205.

Calyx pyriform to elongate pyriform, small, seldom attaining a height of over 1.3 mm., consisting of a low basal circlet in which the sutures are unknown, five elongate radials that make up more than one-half the body height, five orals of nearly equal size, the posterior oral being slightly larger than the other four and, in the adult, an anal series originating on the excavated left shoulder of the *RPR* (Fig. 1, *1–11*). The radials are of almost equal width on young forms but are differentiated with later growth so that the *LAR* is always distinctive by being narrow with almost parallel sides, and the two posterior radials become wider than any of the other three. Immature forms are armless, the outer edges of the orals meeting flush with the outside edges of the radials, the arms being introduced on the *RPR* and *LAR* first, then on the *LPR* and *RAR*, and finally on the *AR*. On the majority of representatives there is one arm to a radial but the radials may be axillary. Oral dome prominent in the young, making up almost one-third of the entire height of calyx, becoming less prominent with growth until on the mature form it makes up about one-sixth of the total height. Orals concave with raised borders, the concavity of the posterior oral being interrupted

near the center of the plate by a short ridge or tubercle that probably represents the hydropore. Anal series introduced about the same time as the formation of the arm facet on the *AR* and originating in an excavation on the left shoulder of the *RPR*. First plate of the anal series long and slender with parallel sides, other anals not preserved. First primibrachs simple, slightly longer than wide, others

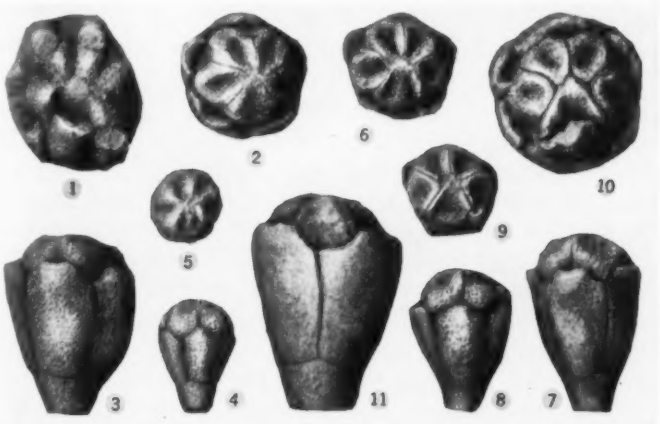


FIG. 1, ILLUSTRATIONS *1–11*.—*Allagecrinus americanus* Rowley. All specimens enlarged twenty-eight diameters. 1. A large individual with brachials in place on *AR*, *LAR*, *RPR*, and anal plate on left shoulder of *RPR*. *2* and *3*. Lateral (*LPR*) and summit views of specimen with five arm facets and slight differentiation of left shoulder of *RPR*. *4* and *5*. Lateral (*RPR*) and summit views of immature armless specimen. *6* and *7*. Lateral (*LPR*) and summit views of specimen with facets on *LAR*, *LPR*, *RPR*, *RAR*, and small facet on *AR*. *8* and *9*. Lateral (*LPR*) and summit views of specimen with facet on *LAR* and first brachial in position on *RPR*. *10* and *11*. Lateral (posterior inter-radius) and summit views of specimen with five arm facets and partially exfoliated anal plate.

not preserved. Ornamentation consists of reticulate meshwork of fairly coarse ridges. The ridges are coarse on the young and become less conspicuous with growth of calyx. Many of the largest forms are almost smooth.

Occurrence.—Shale partings in the lower 3 feet of the Louisiana limestone at the mouth of Buffalo Creek, about one mile south of Louisiana, Missouri.

Figured Specimens.—Catalogue number E-3–5, University of Missouri.

GROWTH-STAGES

The most immature stage of *Allagecrinus americanus* Rowley studied is represented by nine very small specimens, the best preserved of which is illustrated in Figure 1, *4* and *5*. They vary from 0.5 to 0.6 mm. in height and are ornamented by a reticulate meshwork of fairly coarse ridges. This ornamentation is of the same strength on all specimens of this size and on all parts of each specimen so that there is no chance that it was caused by irregular solution or wear. The radials are relatively shorter than in the mature individuals and the oral dome is much more prominent. The radials are all of approximately the same width, but even at this early stage the narrow *LAR* can be readily identified. The posterior radials are of almost exactly the same size as the *RAR* and *AR*. The oral dome is swollen and quite prominent, making up approximately one-third of the height of the entire calyx. The outer edges of the orals are flush with the outer edges of the radials, leaving no possible place for the attachment of arms. There is no anal plate and no evidence that one developed at a later stage. The *RPR* is not differentiated in any way. There is no visible opening into the calyx, although the small knob in the center of the posterior oral (Fig. 1, *5*) is probably the hydropore.

The next recognizable stage shows an increase in height to approximately 0.7 mm. Some thirty specimens of this stage differ from the earlier stage not only in being slightly larger, but in having a slightly less prominent oral dome and by the retreat of the orals from the outer edges of the *RPR* and the *LAR* with the introduction of arm facets. Figure 1, *8* and *9*, show lateral and summit views of a specimen with the first primibrach in position on the *RPR*. The *LAR* and *RPR* are always the first to develop facets, and these two facets are well developed on many specimens in which the outer edges of the other three radials fit closely into the outer edges of the orals. There is no differentiation of the *RPR* at this stage and no evidence of an anal series.

The third stage in the development of *A. americanus* Rowley (Fig. 1, *6* and *7*) is characterized by the introduction of arm facets on

the *RAR* and the *LPR*. Ordinarily these two facets seem to have developed simultaneously, but in rare cases either one developed before the other. The appearance of these two facets is accompanied by an increase in the size of the calyx, a lessening of the prominence of the oral dome and a marked increase in the relative size of the posterior radials. There is, as yet, no definite sign of the anal series of plates or the differentiation of the *RPR* for their reception. All radials, except the anterior, bear arm facets. The ornamentation is still conspicuous.

The last stage (Fig. 1, *10* and *11*), represented by apparently mature individuals, is characterized by the development of an arm facet on the *AR* and the differentiation of the *RPR* by the left shoulder sloping abruptly below the general surface of the radials for the reception of the first plate of the anal series. The anal series and the arm facet on the *AR* may originate simultaneously or either one may develop before the other. This seems to vary greatly on different individuals. In the young forms the oral dome accounted for almost one-third of the entire height of the calyx, but in the mature specimens it makes up only about one-sixth of the total height. There is also a lessening in the strength of the ornamentation and some of the larger forms are almost smooth.

In the original description of *A. americanus*, Rowley[3] notes that the larger specimens among his types possess "scars for the attachment of nine arms." Weller[4] failed to note this stage in his examination of over a hundred individuals of this species, and none of the specimens examined in the preparation of this paper shows more than five arm facets. However, the types have not been re-examined, and considering the tendency for other species of this genus to develop axillary radials, it is quite probable that this stage exists in *A. americanus* Rowley.

In summary, the earliest represented stage of *A. americanus* Rowley consists of a small calyx about 0.5 mm. high with a prominent oral dome, no arm facets, and no anal series. Arm facets are

[3] R. R. Rowley, "Description of a New Genus and Five New Species of Fossils from the Devonian and Sub-Carboniferous Rocks of Missouri," *Amer. Geol.*, Vol. XVI (1895), p. 219.

[4] *Op. cit.*, p. 14.

developed first on the *RPR* and *LAR*, then on the *LPR* and the *RAR*, and finally on the *AR*. Accompanying the introduction of the facet on the *AR* is the development of an anal series on the left shoulder of the *RPR*. These changes are accompanied by an increase in the size of the calyx, a decrease in the strength of the ornamentation, a lessening of the prominence of the oral dome, and a greater differentiation in the width of the radials, the two posterior radials becoming much wider than the other three.

HOW MANY GLACIAL STAGES ARE RECORDED IN NEW ENGLAND?

RICHARD FOSTER FLINT
Yale University

It is said that during the time when the fourfold glacial succession was being established in the Mississippi Valley region, geologists working on the Pleistocene of the Mississippi Valley looked down upon the geologists working on the Pleistocene of New England because of their apparent inability to read in the New England drift an equally long and complex history. It is to the New Englanders' credit that most of them did not read a complex history *into* their drift. The great relief, hilly character, and dominantly resistant rocks of New England, coupled with its lack of a driftless area, and last but by no means least its coastal position (so that much of its drift-border zone has been submerged in the rising postglacial sea), make the recognition and evaluation of pre–Late-Glacial features a more difficult matter than in the low-relief, weak-rock region in the heart of the continent.

The coastal plain, unfortunately now mostly submerged, is the most promising hunting ground in New England for pre–Late-Glacial Pleistocene geology, for two reasons: first, it lies in the drift-border zone, where glacial erosion must have been relatively weak and of short duration, and therefore less likely to destroy earlier deposits; second, it is a region of slight relief, thereby favoring the development of unit features, such as recognizable strata, ice-thrust phenomena, and end moraines, more or less continuously along considerable stretches of ice front. The value of this hunting ground has been recognized in that the glaciated coastal-plain region has been a field of intensive investigation since Shaler's time. The two most modern single studies are represented by the work of M. L. Fuller on Long Island[1] and the contemporaneous but more recently

[1] M. L. Fuller, "The Geology of Long Island, New York," *U.S. Geol. Surv., Prof. Paper 82* (1914).

published study of the Cape Cod district[2] by Woodworth and Wigglesworth. The stratigraphic conclusions reached in the latter work parallel those reached in the former, in that they involve the recognition of four distinct glacial stages separated by interglacials. The writer believes that the local mapping and the local interpretations involved in this work are of a high order, but is not convinced that all the wider interpretations and correlations are justified by the facts. Therefore, in spite of the respect which the nature of the study inspires, certain points involving doubts and disagreements are here discussed, chiefly because the writer claims some familiarity with the geology of Cape Cod and Long Island, and holds somewhat different views, the comparative value of which further study and discussion will determine.

Pleistocene glacial stratigraphy is ordinarily much more complex than, for instance, Paleozoic marine stratigraphy. Changes in lithology and in mode of deposition are apt to be abrupt both laterally and vertically, so that conditions between exposures cannot be inferred with confidence. There are few fossils to aid correlation. The non-consolidated nature of the deposits favors slumping, which quickly covers the faces of exposures, making restudy difficult if not impossible. For these reasons, long-distance correlations of small units are hazardous even after very detailed field study. For example, a general agreement between the Pleistocene glacial stratigraphy of Long Island and that of Cape Cod is expectable, but detailed agreements and continuity of many individual beds along an ice front of 200 miles seem much less likely.

The composite column for Cape Cod as interpreted by Woodworth and Wigglesworth is given in Table I. The points of correspondence with Fuller's Long Island column[3] are immediately apparent.

If these correlations are valid, then we have in the Cape Cod region a remarkably complete representation of the Pleistocene column, as we understand it from the Mississippi Valley region. In the type localities in that region, the basis of separation of the several

[2] J. B. Woodworth and Edward Wigglesworth, "Geography and Geology of the Region Including Cape Cod, the Elizabeth Islands, Nantucket, Marthas Vineyard, No Mans Land and Block Island," *Mem. Harvard Mus. Comp. Zoöl.*, Vol. LIV (1934).

[3] *Op. cit.*, table facing p. 220.

drift sheets consists ideally of (1) tills or other drift deposits of types that are distinctive because they derive from different ice centers, (2) separated by zones of marked weathering and/or distinct interglacial deposits. All the Cape Cod ice evidently came from the Labrador center; hence the Cape Cod drifts cannot be separated on

TABLE I

Cape Cod District	Correlation
Wisconsin deposits (Nantucket and Falmouth moraines and Plymouth interlobate moraine)	Wisconsin
Vineyard erosion interval	Peorian Iowan Sangamon
Manhasset formation { Hempstead gravel Montauk till	Illinoian
Jacob sand (transitional from Gardiners clay)	
Gardiners clay (marine)	Yarmouth
Jameco formation { Moshup till Coarse gravel Boulder bed	Kansan
Mannetto clay-till and gravel Weyquosque glacial sand, and Sankaty (marine) sand Dukes boulder bed	Nebraskan
Aquinnah conglomerate (non-glacial, probably fluvial)	

a regional-lithologic basis. Beyond this, the stratigraphic evidence offered in support of the correlation given above is meager. Let us consider the non-glacial members of the sequence. The Aquinnah conglomerate is preglacial and is therefore of no value in the present discussion. The Sankaty sand, exposed on Nantucket, carries marine invertebrate fossils, but it is locally much contorted and its position in the column is uncertain. Wilson[4] regarded it as transitional upward into the Wisconsin glacial deposits. Fuller[5] placed it in the

[4] J. H. Wilson, *The Glacial History of Nantucket and Cape Cod* (New York, 1906), pp. 29–30.

[5] *Op. cit.*, p. 92.

Manhasset formation, below the Montauk till. Woodworth[6] was inclined to place it much lower in the column, on the ground that the overlying till resembles the Moshup till of Marthas Vineyard. Until the position of the Sankaty beds is agreed upon, we are left with only one horizon of manifestly non-glacial character and undoubted stratigraphic position in the entire column: the Gardiners clay. Not even this bed is surely interglacial. For though in one place[7] Woodworth and Wigglesworth state that this clay "was doubtless laid down during an interglacial stage," they say elsewhere[8] "whether the clay is of interglacial or glacial origin cannot be determined, but it is not necessarily interglacial, for all the conditions requisite to its deposition would have existed when the ice front stood some distance back of this area. . . . . Thus the Gardiners clay is considered a glacial or an interglacial marine deposit. . . . ."

One can scarcely avoid the conclusion, in view of these facts, that the correlation of distinct glacial stages in the Cape Cod region rests on uncertain ground.

The next question concerns the separate identity of the Dukes-Weyquosque-Mannetto sequence and the threefold Jameco sequence, both shown in Table I. Each sequence consists of boulders, gravel, and stony blue clay. The two sequences do not occur in the same section, nor do all three members of one sequence occur in any one section. The two standard sections, both strongly folded and overthrust, occur in the Gay Head cliffs on Marthas Vineyard, and in the Nashaquitsa Cliffs, 5 miles southeast on the same island. The Gay Head section exhibits the Dukes boulder bed, the Mannetto till, and an overlying gravel of doubtful correlation. The Nashaquitsa section exhibits the Weyquosque gravel and the Moshup till. The only other section in which a pre-Gardiners till is mentioned is on No Mans Land, 7 miles south of Gay Head, where a cliff exposes, beneath the Gardiners clay, a till bed referred to the Moshup, although no evidence for this correlation is cited. Thus it appears that all the exposures occur in the same district, that no single section includes more than one pre-Gardiners till, and that the inferred two

[6] Woodworth and Wigglesworth, *op. cit.*, p. 97.

[7] *Ibid.*, p. 50. [8] *Ibid.*, p. 168.

triple sequences exhibit lithologic similarities. Apparently Wigglesworth recognized this, for in describing the Nashaquitsa section he says,[9] "These beds [the Weyquosque and Moshup] therefore resemble the Pleistocene beds in Gay Head, where a bed of stony blue clay simulates [sic] a deposit of till, but the stony blue clay in the Gay Head section is regarded by Professor Woodworth as an older deposit, of Mannetto age."

In the absence of paleontologic evidence, the reason for regarding these two sequences as distinct is not clear to the writer, who submits that on the evidence cited, it is at least equally likely that they should be correlated, as representing a single pre-Gardiners till.

Another question concerns the Vineyard erosion interval, an important element in the column because it is regarded by the authors as the equivalent of at least the Sangamon interglacial of the Mississippi Valley region. Recognition of this interglacial stage of post-Manhasset, pre-Wisconsin date is based on no stratigraphic exposure. According to Woodworth and Wigglesworth[10] the evidence consists of (1) partial adjustment of streams to the ice-deformed surface of pre-Wisconsin beds on Marthas Vineyard, and (2) similarity of certain large valleys between terraces of stratified drift on Marthas Vineyard and Cape Cod, to the valleys forming the harbors between the northern necks of Long Island, regarded by Fuller[11] as records of extensive pre-Wisconsin fluvial excavation. As evidence for an interglacial stage, the points cited seem inadequate for these reasons: (1) Streams may be expected to assume courses consequent on an undulating surface deformed by ice thrust, immediately upon the uncovering of the surface by the ice. (2) The harbors between the northern necks of Long Island have been held by Crosby[12] and Fleming[13] to be of constructional origin, therefore recording little or no erosion, and of Wisconsin date, and the writer, who has examined

[9] *Ibid.*, p. 166.

[10] *Ibid.*, pp. 56, 189, 261–64.

[11] *Op. cit.*, pp. 45, 208.

[12] W. O. Crosby, "Outline of the Geology of Long Island, N.Y.," *Ann. N.Y. Acad. Sci.*, Vol. XVIII (1928), pp. 425–29.

[13] W. L. S. Fleming, "Glacial Geology of Central Long Island," *Amer. Jour. Sci.*, Vol. XXX (1935), pp. 216–38.

them independently, is in agreement with this opinion. The valleys in the Cape Cod region, cited by Woodworth and Wigglesworth, are believed to be of similar character. (3) No weathering at the surface of the Manhasset formation is reported. (4) Sea level should have been relatively high during an interglacial stage, thus providing conditions for marine deposits somewhat like the Gardiners clay, rather than conditions for the deep erosion described. (5) Fleming[14] has pointed to several lines of evidence against the existence of an erosion interval at this time on Long Island.

The problem of the Vineyard interval is closely bound up with the correlation of the Manhasset and Wisconsin deposits. If the Vineyard interval be deprived of the interglacial standing attributed to it by Woodworth and Wigglesworth, it is difficult to understand why the Manhasset formation should be regarded as distinct from the Wisconsin. On this head no evidence, other than the questionable points relating to the Vineyard stage, is adduced. Yet facts mentioned in their memoir point to the desirability of grouping the two within a single glacial stage:

> The boulders in the Montauk [Manhasset] till, which were imbedded in impervious clay, are fairly fresh looking. Many of them are less weathered than the Wisconsin boulders. . . . .[15]
>
> The lithological similarity of the Pleistocene beds is particularly marked in the waterlaid deposits of the Manhasset formation and in the Wisconsin deposits. . . . . The upper and lower members of the Manhasset formation could not be told apart were it not for the bed of till (Montauk till member) that separates them, nor could these two beds of Manhasset gravel be distinguished from the outwash gravel of the Wisconsin stage except by considering the difference in their distribution. The Wisconsin till, although it is usually much sandier than the till member of the Manhasset, is at some places so nearly like the Manhasset till that it can be distinguished only by its position and by the fact that it is separated from the Montauk till by a bed of gravel.[16]

That the Manhasset and Wisconsin deposits in Long Island are referable to a single glacial stage has been specifically held by Crosby,[17] Fleming,[18] and Wells.[19] The writer's own field study has

[14] *Ibid.* [15] Woodworth and Wigglesworth, *op. cit.*, p. 55.

[16] *Ibid.*, p. 137. [17] *Op. cit.* [18] *Op. cit.*

[19] F. G. Wells, "Reconsideration of the Pleistocene Geology of Long Island," Geol. Soc. Amer., December meeting, 1934 (abst.).

led him also to this view. As the Manhasset and Wisconsin deposits in the Cape Cod region are in general much like those of Long Island, definite evidence of separate identity must be made available before they can be widely regarded as distinct.

If these criticisms are valid, at most only two glacial stages, instead of four, are represented in the Cape Cod Pleistocene column. Even the Gardiners clay, the most distinctive member of the sequence, on the showing of Woodworth and Wigglesworth, is not certainly of interglacial character, although MacClintock and Richards[20] have recently suggested its correlation with the Cape May formation of New Jersey, a deposit having a marine phase with a warm-habitat fauna. But in spite of the doubt, the Gardiners clay is definitely marine and reasonably distinctive, and therefore serves as a kind of key bed or reference bed. Below it we have at least one till; above it we have at least the Wisconsin sequence. There are intervening unconformities, to be sure, but in the narrow ice-margin zone of the Cape Cod region, repeated short-term oscillations of the ice front must be regarded as likely, and the unconformities are of a type attributable to this mechanism.

This fact should not be lost sight of: The pre-Wisconsin history of the Cape Cod region has necessarily been interpreted thus far on a basis of the very few sections exposed, most of them greatly deformed. As fresh sections appear in wave-cut cliffs we can add to our information. The small body of data now at hand seems to call for the adoption of a conservative attitude—for description in local terms divorced from long-range correlation, which, until supported by stronger evidence than is yet available, will hinder with one hand, while it aids with the other, the clear understanding of the Pleistocene history of northeastern North America.

[20] P. MacClintock and H. G. Richards, "Correlation of Marine and Glacial Pleistocene Deposits of the Middle Atlantic Seaboard," Geol. Soc. Amer., December meeting, 1934 (abst.).

DAVID WHITE

Dr. David White, for many years a valued associate editor of the *Journal of Geology*, died at his home in Washington, D.C., February 7, 1935, at the age of seventy-two.

White obtained his elementary education in country schools near his birthplace in Palmyra Township, Wayne County, New York, and prepared for college at Marion Collegiate Institute, where, under an inspiring teacher, he developed an enthusiastic interest in the systematic botany of the region. His academic training in geology and paleontology was received under Samuel Gardner Williams, Charles L. Prosser, and Henry S. Williams, at Cornell University, where he won early recognition as an exceptional student in such diverse subjects as geology, drawing, and veterinary science.

White's training in botany, geology, and drawing prepared him for service in the United States Geological Survey, where his first assignment, in 1886, immediately after graduation from Cornell, was to make accurate pencil drawings of fossil plants for Lester F. Ward, then in charge of the paleobotanic work of the Survey. Ward had developed a method of using drawings of selected specimens, rather than the fossils themselves, in making systematic comparisons for purposes of identification and description. White was soon placed in charge of this illustrating and a little later was given direction of the extensive bibliographic work in paleobotany that Ward was then inaugurating.

In the early nineties Ward and Fontaine were actively investigating the earlier Mesozoic floras, and Knowlton was describing the floras of the Tertiary and the Upper Cretaceous; but the very important field of Paleozoic paleobotany was practically unoccupied, as far as the Geological Survey was concerned, until White made it his own. Beginning in the Appalachian coal fields where the Geological Survey was then actively engaged in areal mapping, White took up the field and laboratory study of the floras and their stratigraphic relations with the enthusiastic energy and thoroughness that was characteristic of everything he did. Working in close co-

operation with the geologists who were mapping the coal fields, he was soon able to convince them that from his knowledge of the associated floras and their distribution he could not only classify and correlate the formations from field to field over large areas but could also often identify individual coal beds throughout a field, and thus solve problems of stratigraphy, structure, and correlation where other lines of evidence were obscure or misleading. His field studies in paleobotany were extended to New England, the Mississippi Valley, the Southwest, and in later years to the Rocky Mountains and the Grand Canyon region. They embraced the entire Paleozoic and extended into the pre-Cambrian, though his major interest in paleobotany was the Pottsville (early Pennsylvanian) flora, which he studied as opportunity offered throughout his professional career. A large part of this flora as developed in Illinois and neighboring states was described in a manuscript monograph which was nearing completion when his last day's work ended.

White's pre-eminence as a paleobotanist and stratigrapher is unquestioned, but his original contributions to general geology and his personal influence on the development of the science extended into much broader fields. He could not escape the burden of administrative work that so often comes to scientific men who are attached to government bureaus and educational institutions, but to him the added responsibilities and routine duties were only a stimulus to undertake and direct other lines of research. In the Geological Survey he supervised the geologic work in eastern coal fields, then had general direction of surveys in oil and gas fields, and served for ten years, including the World War period, as chief geologist. His much-desired return to paleobotanic research was again delayed by three busy years of service as chairman of the Division of Geology and Geography in the National Research Council and by special duties in the National Academy of Sciences, first as home secretary and afterward as vice-president. Even in the midst of these varied duties, he was making important contributions to isostasy and to the development of methods by which the essential data needed for its problems may be collected; he was demonstrating the important aid that geology may give a nation in the economic crisis caused by war; and he was doing pioneer work on the origin and evolution of coal

and petroleum. In connection with the latter studies he made a very important generalization about the relation between possible oil production and the fixed carbon ratio of associated coals, to the effect that commercial production of oil should not be expected from rocks associated with or underlying coals in which the regional alteration had brought the fixed carbon up to 65 or 70 per cent of the coal, reckoned as pure coal without ash. This carbon-ratio theory, which should prevent enormous waste of capital in many areas where exploration for oil would be profitless, was first announced in the *Journal of the Washington Academy of Sciences*, Vol. V (1915), p. 212, and was more fully elaborated and revised in a posthumous paper in the *Bulletin of the American Association of Petroleum Geologists* (May, 1935).

The many honors that came to Dr. White in recognition of his scientific work have been enumerated elsewhere. They were all deserved. Adored by members of his own household, loved by those privileged to be his close associates, honored by all who knew him, David White met the essential requirements of religion, in that throughout his life he obeyed the injunction to do justly, to love mercy, and to walk humbly with his God.

T. W. STANTON

REVIEWS

Geology of Vitilevu, Fiji. By HARRY S. LADD. Bernice P. Bishop Museum Bull. 119. Honolulu: Museum, 1934. Pp. 263; figs. 11; pls. 44; tables 7.

Fiji affords an interesting field both to the general geologist and particularly to the student of Pacific paleontology because of a rather general belief that it is of continental origin. Lithologically the islands of the Fiji archipelago combine various rock types commonly associated with continental masses, together with others which characterize the volcanic islands of the mid-Pacific.

The rocks of Vitilevu comprise a pre-Tertiary series of plutonics and more or less metamorphosed volcanics and sediments, which form the core of the island, and a younger series of relatively unaltered rocks of Tertiary age. The plutonics include granite, quartz-monzonite, quartz-diorite, diorite, and gabbro, though these types are much more closely related petrographically than their names indicate. Most of them are fine-medium to medium grained. Some of the metamorphic rocks which they intrude exhibit a slaty structure, but schists and gneisses are absent.

The younger series is composed predominantly of pyroclastic material, much of it reworked. The Viti formation in the middle of the series is primarily a massive foraminiferal limestone reaching 200–300 feet in thickness. Corals are almost entirely wanting, suggesting that this limestone of early Miocene age was deposited on a sea floor below the depth of reef-coral growth. Volcanic activity continued into the Pleistocene but died out before its close.

The author distinguishes between "oceanic islands, composed entirely of volcanic rocks and organic limestone, or sediments derived from these," and "continental islands made up of plutonic or metamorphic rocks in addition to the types of rock found on oceanic islands. . . . . As shown on the map (Fig. 6), all of the continental islands lie west of an imaginary line drawn from Yap southeastward through Truk, New Ireland, the Solomon Islands, and Fiji to Tonga, thence southwestward through the Kermadecs to include New Zealand and certain of its outlying islands." Because of this observation the author extends the Philippines, East Indies, and Australia out to this line to comprise "the former Melanesian continent." This continent is treated as if its verity were established.

Its heart is Australia; within an arc swinging from Borneo through New Guinea, New Zealand, and Tasmania, Paleozoic rocks are found; and within the arcuate imaginary outer line, postulated as the boundary of the continent, Mesozoic rocks occur.

"The destruction of the Melanesian continent was one of the major events of earth history." But how did it take place? Normal faulting due to tension is suggested by the author. One may well wonder, however, how to picture the dropping of such vast areas thousands of feet by normal faulting and what became of the underlying rock material. The areas now submerged to abysmal depths are of much greater extent than the island ridges. What made the ridges now relatively so high standing? Dynamically and mechanically this concept seems to the reviewer a difficult one to accept.

Is it not simpler to regard the individual island ridges as upfolded strips of ocean floor arising from the depths? Not a few of them seem to be comparable in magnitude to the Sierra Nevada Mountains of California where schists and gneisses (absent in Vitilevu) were strongly developed and great masses of granodiorite were injected as batholiths. Can it be affirmed confidently that the chemical composition of the Vitilevu plutonics is such that they could not have come from beneath the Pacific? Australia was a continental mass as early as pre-Cambrian times, exhibiting rocks contorted in pre-Paleozoic orogenies. The inner zone of surrounding islands (Borneo, New Guinea, New Zealand, and Tasmania) contains Paleozoic rocks. Early upfoldings of the necessary strips of the ocean floor at appropriate times would explain this fact. The islands of the outer belt contain Mesozoic rocks. Later upfoldings would explain this. Perhaps we see a continent in the process of development, growing and enlarging outward from the Australian shield by successive increments of folding, rather than an old continent undergoing dismemberment. This alternative is not considered in the discussion. Under either hypothesis, extensive faulting is to be expected in strips of islands undergoing deformation, and the extravasation of lavas and outbursts of pyroclastics are the natural accompaniment.

The bulletin also contains sections on the petrography, by Arthur A. Pegan; smaller foraminifera, by Joseph A. Cushman; larger foraminifera, by G. Leslie Whipple; corals, by J. Edward Hoffmeister; smaller echinoids, by H. L. Hawkins; and decapod crustaceans, by Mary J. Rathbun.

It is interesting to note that the Fijian faunas are more closely related to the Tertiary faunas of the tropical East Indies than to those from sections in New Zealand and Australia which lie somewhat closer but in more

southerly latitudes. "Eventually, with the aid of intermediate localities such as those in India, it may be possible to correlate the late Tertiary sections of the southwest Pacific with those of Europe in a satisfactory manner, but at the present time it is impossible to say with any assurance that what is called Miocene in the East Indies is the exact equivalent of what is defined as Miocene in the type sections of Europe." The term "Miocene" is accordingly used in this report for what has been called Miocene in the East Indies. Many species of invertebrates have been described and figured in plates and not a few new species added.

The bulletin is a comprehensive, well-rounded piece of work of much interest and unusual value because of the important contributions which it makes to many different geologic problems. The natural difficulties confronting the field geologist in Vitilevu, which can be appreciated by anyone who has visited the island, make the successful accomplishment of this systematic study a notable achievement.

R. T. C.

Um das geologische Weltbild. By ERICH HAARMANN, Berlin. Stuttgart: Ferdinand Enke, 1935. Pp. xi+108; figs. 23; map 1. Rm. 5.80.

CONTENTS

1. Introduction
2. Only a few fundamental concepts of geology are completely established
3. The lack of adequate training in physical thought
   a) The loose application of physical terms and the lack of clearness of physical conceptions
   b) The geologist and physics
4. Are mechanical laws applicable to the earth's crust?
5. Mechanical properties of the crust
   a) The multitude of variables
   b) Anisotropy of the crust
   c) Does the mosaic of the crust consist of rigid and mobile blocks?
   d) The anisotropic crust is in its totality quasi-isotropic
6. The registration and reproduction apparatus "man"
7. Review
8. Preview
9. Footnotes, literature, register, etc.

Haarmann's book is an appeal to all geologists for self-criticism. Without attempting to discuss geologic theories comprehensively in textbook style, the author aims at the weakest points of our conceptions and stimulates thinking. Our geologic ideas change from time to time and are large-

ly influenced by the *Zeitgeist* to which we all are subject. Whatever seemed adequate yesterday may be absurd tomorrow. A concept may be destroyed while being built up, through increasing knowledge. "Be critical against yourself and learn to take criticism from others; co-operate and do not think that you are dealing with facts because you deal with interpretations of masters." Study the evolution of ideas in the history of geology and "you may realize that your followers may laugh about you as they do about the description of a reptile skeleton as being the remainder of a bedeviled human."

Haarmann calls for greater clarity in thinking and more accuracy in the application of the laws of physics in geologic interpretation. Less specialization is needed. An overspecialized geologist is not likely to arrive at a broad conception; he is chiefly a technician.

Whoever uses an instrument, knows its constants and corrections, but few geologists seem to care about their own "constants" and personal factors.

Haarmann also says: "Errors are not gallows, but waymarks." We learn through our mistakes, but only if we recognize them.

The little book is very well written: indirect or involved language is carefully avoided. Good illustrations may help the non-German reader considerably. It seems to the reviewer that this appeal should find many followers.

ERNST CLOOS

On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland, Part III: *The Aland Islands*. By J. J. SEDERHOLM. Bulletin de la Commission Géologique de Finlande No. 107. Helsingfors: Government Press, 1934. Pp. 68; figs. 43; maps 2.

This paper is one of the last works of the late Professor J. J. Sederholm. In it he continues his systematic study of the effects of granite invasion into various types of country rocks, discussing, as in the other papers of this series, not only the migmatites but all the rocks of the area. Emphasis is placed on petrology, the complicated structure being left for future study. Described at length are certain lamprophyric rocks associated with the earliest of the three Archean granites, and the Enklinge series (Bothnian) of sediments and volcanics. While having mainly a granitic composition, these islands show small but important areas of sedimentary and volcanic rocks. All but the latest (post-Archean) rocks are very highly metamorphosed.

ROBERT GROGAN

VOLUME XLIII NUMBER 8, PART I

THE

JOURNAL OF GEOLOGY

November-December 1935

SUPPLEMENTARY NUMBER

SYSTEMATIC PACKING OF SPHERES—WITH PARTICULAR RELATION TO POROSITY AND PERMEABILITY

L. C. GRATON
Harvard University
AND
H. J. FRASER
California Institute of Technology

ABSTRACT

Geometrically systematic arrangements of uniform spheres are searchingly investigated in Part I. The relationships disclosed, important wherever orderly distribution of points or particles is involved, are here especially treated as the *underlying principles* of porosity and permeability. Besides packings defined respectively as "chaotic," "haphazard," and "chance," six cases of simple, systematic packing are recognized; two are orientation variants, but four are independent arrangements and include the two hitherto described: "loosest" and "tightest." Striking symmetries appear, and close analogies to crystal structure, including twinned and tripled arrangements.

The unit void of each case is thoroughly explored and illustrated, since in it lies the key to porosity and permeability. The stability of the several cases and their probabilities of being formed indicate that Case 6, tightest or rhombohedral, is most favored, and this is abundantly confirmed by experiment. The commonest natural packing, however, comprises colonies of Case 6 packing strewn in a surrounding mesh of haphazard, the whole constituting chance packing; the practical consequences of such arrangement are discussed. Translation from one packing to another is treated, and its bearing on dilatation outlined.

Part II considers permeability in all its relations to porosity, including the elements and degrees of dependence and independence. Geometry of the intersphere voids receives particular attention as affecting fluid flow through them; and plentiful graphs of the surprisingly complex void sections are shown, as well as of their integrated projections which somewhat influence rectilinear flow. Effect of assemblage orientation on flow is emphasized. Since permeability is of vectorial quality, every systematic assemblage of spheres is *anisotropic* with respect to permeability; therefore, if a single value is to be used for permeability, it must be the *mean* value.

It is concluded that experiment must still be relied on for determining permeability, since no existing means permit its *exact* computation. The Slichter formula and that by Fair and Hatch, both founded on the law of Poiseuille and aiming to state permeability in terms of porosity, are examined critically and found to yield only approximations, largely because of their deficient regard for details and effects of void geometry. However, comparative tabulation gives best available data on porosity and permeability of the several cases. This discloses the enormous differences in permeability caused by differences in packing, including effects of container walls and of included larger units (e.g., as in conglomerates). The varied effects of void geometry on capillary phenomena are discussed. Plea is made for further mathematical study of permeability, toward which the present paper may be helpful in contributing a geometrical basis.

TABLE OF CONTENTS

PAGE

INTRODUCTION 787
Scope of Paper 787
Historical Perspective 788

PART I. CONSIDERATIONS ESPECIALLY AFFECTING POROSITY 790
Essential Definitions 790
Geometry of the Six Packings 792
General Relationships 792
Nature of the Unit Cell 797
Description of the Individual Packings 801
Geometry of the Voids 804
General Considerations 804
The Unit Voids 807
Twinned and Tripled Packings 815
Relative Stability of the Various Packings 820
Probability Factors for the Various Packings 828
Building of the Layer 828
Effects of Other Influences 837
Effect of Container Wall 839

PART II. CONSIDERATIONS ESPECIALLY AFFECTING PERMEABILITY . . 849
The Significance of Permeability 849
The Intersphere Voids as Channelways 851
Permeability Characteristics of the Unit Void 852
Change in Cross-Sectional Area 852
Change in Shape of Cross Section 858
Divided and Re-united Flow 859
Curvilinear Flow 860
Diagonal Flow 861
Effect of Twinning and Tripling 866
Summation of Effects 868
Permeability of Haphazard Packing 875
Magnitude of Permeability 875
Orientation of Permeability 878

PAGE
Permeability of Chance Packing 879
Effect of Container Wall 887
Slichter's Formula for Flow 889
Formula of Fair and Hatch 897
Manner of Derivation 898
Limitations of the Formula 901
Capillary Phenomena 904

Introduction

Scope of Paper

For several years the authors have been examining, by various means and from diverse aspects, the highly important properties of porosity and permeability of rocks. A substantial portion of the results is set forth in the paper which immediately follows: "Experimental Study of the Porosity and Permeability of Clastic Sediments,"[1] by H. J. Fraser. The present discussion is introductory to the more strictly geological treatment of that paper; it investigates some of the fundamental space relationships that bring into being these particular properties of rocks and that must underlie a sound conception of these properties. But these same space relationships, surprisingly varied, and at the same time beautifully systematic, have wider application, as in elasticity, crystal structure, and similar fields that involve orderly arrangement of points or particles.

More specifically, this paper deals with the geometry of various ideal and near-ideal assemblages of discrete, ideal spheres; and it treats them primarily from the abstract geometrical standpoint, as if it made no difference whether the units were marbles, atoms, or planets, or whether they were assembled by man, machine, or Nature. The ideal abstractions here developed are, in the paper that follows, used and interpreted with due regard to the geological materials and processes actually concerned, and therefore with appropriate consideration for all those departures from the ideal which may or must be involved in natural rocks of clastic origin.

The conditions under which this investigation of porosity and permeability were conducted and acknowledgment of the support which made it possible are given in the following paper. With re-

[1] *Jour. Geol.*, Vol. XLIII (1935), pp. 910–1010.

spect to that portion of the entire subject embraced within the limits of this introductory article, we wish to express our indebtedness and thanks to several of our Harvard colleagues, especially the following: the late Professor O. D. Kellogg, for assistance in the mathematical study of packing; Professor G. M. Fair, for valuable criticism in regard to flow; Dr. H. H. Lester, for certain ideas regarding analogies to the crystal space-lattice; Dr. M. A. Peacock, for crystallographic guidance; and Mr. E. B. Dane, Jr., for many helpful suggestions and for collaboration with the illustrations.

HISTORICAL PERSPECTIVE

Systematic arrangements in space have long been subjects of scholarly inquiry. Since the classic contribution of Haüy in 1784, mineralogists and crystallographers have given much consideration to the space arrangement of atoms and molecules in crystals; and especially since the revelations of internal structure by means of X-rays and the attendant defining and improvement of the conception of the crystal space-lattice, a great deal has been learned by crystallographers and physicists regarding systematic atomic arrangements. Analogous, though more restricted, considerations have been pursued by the chemists in their efforts to understand the space-constitution of chemical compounds, the meaning of isomerism, the cause of polarization by liquids, etc. The engineers, physicists, and mathematicians have followed somewhat similar approaches in their investigations of physical and optical elasticity and related considerations regarding the solid state. The mathematicians have pursued this general line of inquiry into the realm of pure geometry, in dealing with the homogeneous partition of space and the ideal conceptions of point arrangement. Finally, the geologists, the hydrologists, the students of soils, and the civil and the sanitary engineers have, with some help from physicists and mathematicians, attacked the problem of arrangement or packing of solid particles with particular reference to the topics of major interest in this paper, viz., porosity and permeability of natural materials, as affecting water supply, migration of oil and gas, plant growth, foundations, filtration, and drainage.

From these varied sources an imposing bibliography could be as-

sembled relating more or less directly to this question of the packing of solid units, and embracing, among countless others, the names of such outstanding investigators as Haüy, Frankenheim, Delafosse, Bravais, Sohncke, Federow, Laue, the Braggs, Pasteur, Kékulé, William Barlow, Lord Kelvin, C. S. Slichter, and many others.

It might be expected, therefore, that the subject of arrangement of units in space has by this time been thoroughly explored and that a sound and complete lot of principles would now be available for use in any specific applications that might arise, in the same way that the multiplication table or the list of atomic weights is at hand, ready-made for whoever has use thereof. Strangely enough, this does not appear to be the case. It was not until an even hundred years after Haüy's first incursion into this general field that William Barlow[2] pointed out that analysis of the manner of arranging solid units to form component aggregates may best be approached by dealing with the most ideal case possible, viz., that in which the units consist of spheres of uniform size. Such delay in recognition of a fact that now seems self-evident can be explained only on the presumption that prior investigators had envisaged the problem only in a narrow, piecemeal fashion. The same seems to be true to some extent of Barlow himself and of those who have followed him.

In consequence, for one reason or another, preceding treatments do not seem to be at the same time directly applicable and wholly satisfactory with respect to the present problem, which, as elaborated later, is concerned with those simplest assemblages of uniform spheres so arranged that the spheres mutually support one another. Some of these earlier analyses do not fit our present problem because the arrangement concerned is due to "forces" or "bonds" which give inherently different spacings from those that result from the mere condition of mutual physical support afforded by tangency of sphere surfaces. To a similar category must go those cases that envisage interpenetration instead of rigid mutual exclusion of adjacent units. In other cases, special heterogeneities of size and shape of the particular units involved bring departures from the fruitful pathway of consideration of our particular subject. Other presentations give only restricted or incomplete consideration of the possibilities perti-

[2] *Nature*, Vol. XXIX (1884), pp. 186–88, 205–7.

nent to our problem and are especially deficient with respect to the matter of highest importance in the present connection, viz., the shape and arrangement of the intersphere voids. Still other analyses appear to contain outright errors.

Therefore, because of this apparent absence of a direct, but adequate, exposition of the systematic packing of spheres and because of the great light shed on the nature and variations of porosity and permeability by such means, it is here undertaken to set forth an analysis of those cases of systematic packing of uniform spheres which seem to have direct and practical relation to the porosity-permeability problem. This analysis is furthermore believed by us to be of more general nature and more complete from the geometrical standpoints than prior treatments have been. It may therefore possibly be found of wider interest and use than in specific relation to porosity and permeability.

Part I. Considerations Especially Affecting Porosity

Essential definitions

For present purposes, certain definitions are required, as below.

The term *packing* will here be applied to any manner of arrangement of solid units in which each constituent unit is supported and held in place in the earth's gravitational field by tangent contact with its neighbors. From what has been said shortly above, it will be evident that this is a more restricted sense of the term "packing" than that in which it is often employed in such geometrical analyses.

The *unit solid* is an ideal sphere of radius R.

The packing of uniform spheres may be either *disorderly* or constantly repetitive, i.e., *geometrically systematic*. It will be advantageous first to consider the several simplest types of systematic packing and then to examine the deviations that become more and more complex and chaotic.

The *row* is an aggregate of uniform spheres arranged with their centers along a straight line and successively spaced at the distance of $2R$, so that each sphere along this line is tangent to its neighbors on either side.

A *set of rows* is an assemblage of rows in parallel direction. The rows in a set may be spaced closely or widely with respect to one

another; and they may lie in a single plane or in more than one plane, but in the latter case the planes must intersect in lines parallel to the rows.

The *layer* (closely corresponding to the *plane net* of space-lattice terminology) is a parallel arrangement of rows in the same plane and so spaced that the spheres in each row are tangent to the corresponding spheres in adjacent parallel rows. As a result of this condition of tangency, it follows that a second (and in some cases a third) set or direction of rows is established, so that each layer comprises two (or three) sets or directions of rows.

There are various types of layers, depending upon the angle of intersection of the sets of rows in the layer. But it will be seen that

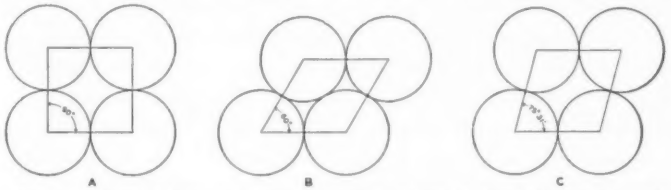


FIG. 1.—Types of layers. *A*, square layer; *B*, "simple" rhombic layer; *C*, special rhombic layer.

under the condition of mutual tangency of spheres in a row, the angle at which two sets of rows intersect must lie between values of 60° and 90°. The type of layer that seems most natural and familiar (like the layout of trees in an orchard) is that in which two sets of rows intersect at 90°. This may be called the *square layer*. See Figure 1, *A*.

The next most familiar and simple type of layer is that in which three sets of rows intersect at 60°. This may be called the *simple rhombic layer*.[3] See Figure 1, *B*.

Layers are possible in which the sets of rows have any angle of intersection between these limiting values of 60° and 90°; but only the square layer and the simple rhombic layer will be given general consideration[4] here, since it appears that these two are adequate to

[3] The "simple rhomb" is here defined as one in which the short diagonal is of the same length as a side, and the ratio of diagonals is 1:1.73 (i.e., $1:\sqrt{3}$).

[4] One other kind of layer that results under certain circumstances from the stacking of simple rhombic layers is discussed later and is shown in Fig. 1, *C*.

represent the limiting types of systematic packing actually encountered. The layer is here emphasized particularly because of its fundamental influence on the resulting packing.

The *body* is a stack of parallel layers so arranged that the spheres in one layer are tangent to corresponding spheres in adjacent layers. See page 828 for definition of *colony*.

The *unit cell* is that smallest portion of a body (as just defined) which gives complete representation of the manner of packing and of the distribution of voids throughout that body. Its analogy to the unit cell of crystallography is evident. More explicit definition is given on page 797.

The *unit void* is the void contained within the unit cell. It is further specified on pages 807–8.

By giving consideration to the centers of the spheres involved, the unit solid may be visualized as a *point*, the row as a *linear* arrangement, the layer as a *plane* arrangement, and the body as a solid or *three-dimensional* arrangement. It is only to the three-dimensional arrangement that *packing* applies in the sense here entertained. Systematic packing of the kind here considered is achieved by various simple arrangements of either the square layer or the simple rhombic layer; such packing may be designated *simple systematic packing*. There could be systematic arrangements of layers intermediate between the square and the simple rhombic; but these would give intermediate values of porosity and permeability and therefore need not be considered in detail. See pages 827–28 for definitions of *chaotic* packing, *haphazard* packing, and *chance* packing.

GEOMETRY OF THE SIX PACKINGS

GENERAL RELATIONSHIPS

It has been generally customary hitherto—at least in connection with porosity and permeability—to recognize and consider only two kinds of systematic packing, often called, respectively, "loosest" and "tightest" packing. But while these two represent the opposite limits possible in simple systematic packing, consideration of only these two extreme cases involves an unjustifiable neglect of certain equally systematic but intermediate modes of packing.

As a matter of fact, it proves that there are three geometrically simple ways of stacking either square layers or simple rhombic layers upon one another. Therefore, there are three geometrically simple schemes of systematic packing for each of the two simple types of layers making six schemes in all. But it develops that two of the three ways of stacking the square layers are respectively identical in packing (though of different orientation in space) with two of the three ways of stacking the simple rhombic layers; so there are, in fact, only *four different*[5] simple and systematic ways of packing within the limitations already mentioned.

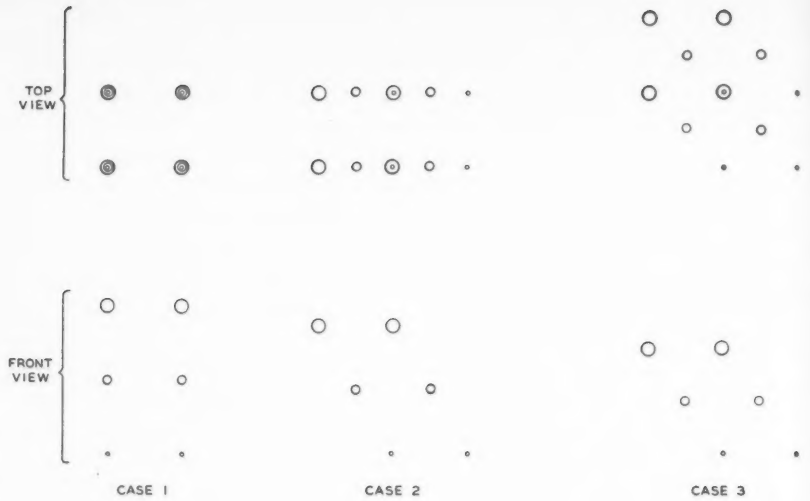
The manner in which these several packings are attained is shown in the following key diagram, Figure 2. In each of the six cases there shown, the smallest circles locate the centers of spheres of the lowest, or first, layer; the intermediate circles locate similarly the centers of corresponding spheres of the next-overlying, or second, layer; and the largest circles locate the centers of spheres of the third layer. Comparison of the top and the front views in each case will indicate the three-dimensional relations of the layers to one another. In the diagram, only four spheres are indicated in each layer; but the layers may actually be extended indefinitely, if holding to the square or simple rhombic pattern, respectively. Also, only three layers are indicated in each case, but additional layers may be added indefinitely by stacking each successive layer on the one next below in the same manner that the second layer is stacked on the first. For convenience in description, the conventional assumption is made that in all cases the *stacked* layers are horizontal; but newly produced layers resulting from the stacking may have different attitudes with respect to the horizontal basement.[6]

The diagram of Figure 2 shows that for each of the two simple types of layers the three simple arrangements are:

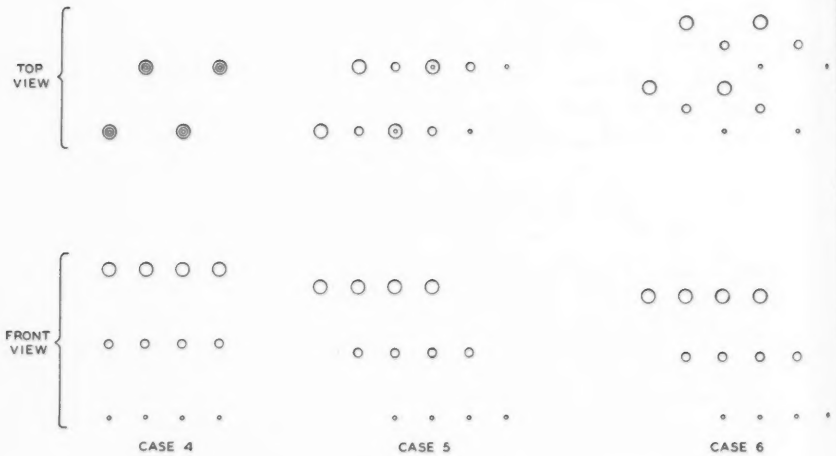
I. Cases 1 and 4—spheres in second layer vertically over those in first layer.

[5] It will appear later, in connection with the discussion of twinned and tripled packings, why it is desirable to carry through the discussion on the basis of the *six* cases instead of on the basis of the fundamentally different *four*.

[6] For example, in Case 1, formed by stacking horizontal square layers vertically over one another, two sets of square layers in vertical attitude and mutually at right angles are produced.



A. ARRANGEMENT OF SQUARE LAYERS



B. ARRANGEMENT OF SIMPLE RHOMBIC LAYERS

FIG. 2.—The six schemes of stacking simple layers

II. Cases 2 and 5—spheres in second layer horizontally offset with respect to those of the first layer, by a distance R along the direction of one of the sets of rows.

III. Cases 3 and 6—spheres in second layer horizontally offset with respect to those of the first layer, in a direction bisecting the angle between two sets of rows and by a distance of $R\sqrt{2}$ in Case 3 and of $2R\sqrt{1/3}$ in Case 6.

In Figure 3 is illustrated the essence of each of the six cases, represented in each instance by an assemblage of eight spheres, four in each of two layers that are stacked one on top of the other. The groupings in Cases 1, 2, and 3, shown in perspective, are depicted in the attitude of resting on the square layer, and Cases 4, 5, and 6 on the simple rhombic layer.

These several modes of packing have certain simple geometrical relationships to one another. These relationships involve internal arrangements and external shapes that are analogous to various crystal forms. A tabulation of these relationships is given in Table I; each case is given the name of its general crystal analogue.

In Table I the line headed "Spacing of layers" represents the vertical distance from the horizontal plane passing through the sphere-centers of one layer to the corresponding plane of the next layer. It is evident that, although there is no interpenetration of spheres, there is interpenetration of layers in all of the arrangements except Cases 1 and 4, as a consequence of the placing of spheres of one layer into the cuspate or hopper-like depressions between spheres of the adjacent layer. The line headed "Tangent neighbors" relates to the number of spheres which each sphere touches. In the square layer, each sphere touches four neighbors in that layer; and, depending on the arrangement of the layers, it is touched also by one, two, or three spheres of the layer next above and of the layer next below. In the simple rhombic layer each sphere touches six neighbors in the same layer, and likewise one, two or three spheres of the layer next above and of the layer next below. (In the special rhombic layer mentioned on page 803, which develops from a certain method of piling simple rhombic layers, each sphere touches four neighbors in its own layer and one or two—but never three—

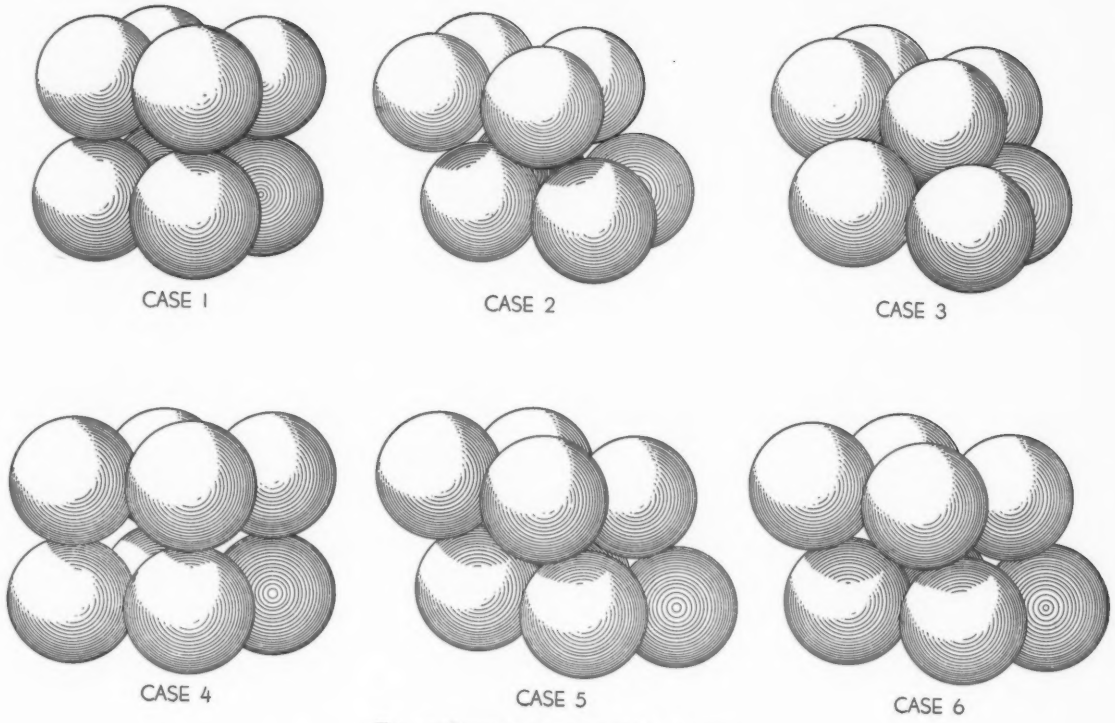


FIG. 3.—Type sphere groups of the six cases

spheres in each of the two adjacent layers.) It thus follows that the minimum number of tangent neighbors in any simple systematic scheme of packing is six (Case 1) and the maximum possible number is twelve (Cases 3 and 6).

TABLE I

GEOMETRICAL RELATIONSHIPS OF THE VARIOUS PACKINGS

ARRANGEMENTS OF SQUARE LAYERS

	Case 1	Case 2	Case 3
Name (crystal analogue)	Cubic	Orthorhombic	Rhombohedral
Spacing of layers	$R\sqrt{4}$	$R\sqrt{3}$	$R\sqrt{2}$
Tangent neighbors	6	8	12
Face angles	90°	90°, 60°–120°	90°, 60°–120°
Interfacial angles	90°	90°, 60°–120°	54°44′–125°16′

ARRANGEMENTS OF SIMPLE RHOMBIC LAYERS

	Case 4	Case 5	Case 6
Name	Orthorhombic	{Tetragonal- / Sphenoidal}	Rhombohedral
Spacing of layers	$R\sqrt{4}$	$R\sqrt{3}$	$2R\sqrt{2/3}$
Tangent neighbors	8	10	12
Face angles	90°, 60°–120°	{60°–120° / 75°31′–104°29′}	60°–120°
Interfacial angles	90°, 60°–120°	{90° / 63°26′–116°34′}	70°32′–109°28′

NATURE OF THE UNIT CELL

Before individual consideration of the six cases of packing, further description is desirable and is now possible for the unit cell, beyond that already given in the list of definitions on page 792. The unit cell may be defined from two standpoints: (1) it is bounded by planes so passed through the centers of adjacent spheres that the resulting polyhedral form meets the requirement of being the smallest possible sample that will completely represent the manner of packing and of void distribution throughout the body of which it is a part; or (2), it may meet the foregoing requirement plus the added stipulation that it also completely represent the *orientation* of void distribution

throughout the body.[7] The cell as considered from the first of these standpoints may be called the *minimum cell;* that considered from the second standpoint may be designated the *complete cell*, and this latter is the unit cell in the general sense.

As a matter of fact, the minimum cell, is identical with the complete cell in three of the schemes of packing, i.e., Cases 1, 3, and 6, since in these, when shape and distribution are determined, orientation is fixed also. But this is not true in the remaining cases. The effect of adding the requirement regarding orientation, as under (2) above, may be explained as follows. In the packing of Case 2, for example, as will shortly appear, the essence of sphere arrangement and of void distribution is typified by a five-sided cell having the

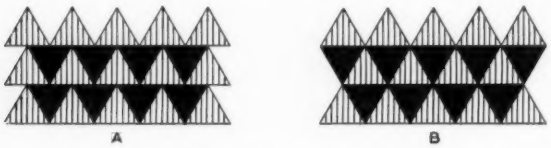


FIG. 4.—Relation of minimum cell to complete unit cell of Case 2

shape of a right trigonal prism, i.e., three square sides and two equilateral triangular ends. But if cells of such shape were assembled together all in the same orientation to make a multi-celled body, they would *fill only half the space* within which they are assembled. In order that the space be completely filled, an equal additional number of identical cells would be required, in an attitude appropriately rotated with respect to the first lot and arranged alternately therewith. This is indicated (in two different patterns) by Figure 4, in which the hatched areas represent the ends of the trigonal prisms in one attitude and the solid black areas represent the ends of the trigonal prisms in the rotated attitude. Such a right trigonal cell, therefore, does not fully comprehend and represent the factor of orientation. In order to have, for Case 2, a cell which will embrace both the shape factor and the orientation factor, it must consist of

[7] In discussing a closely analogous relationship, Lord Kelvin expressed the two requirements here involved as "the same shape and sameways oriented" (*Proc. Roy. Soc. London*, Vol. LV [1894], p. 1).

two right trigonal prisms so rotated with respect to one another as to be joined along a prism face. As so joined, the two right trigonal prisms would now collectively constitute a six-sided form or cell, an orthorhombic prism having four square sides and two simple rhombic ends. Such cells, when packed close together in parallel orientation, will completely fill the space and will thus produce a solid body (cf. Fig. 4, *B*). The right trigonal prism is thus the minimum cell of Case 2; and the orthorhombic prism is the complete cell of Case 2. The same holds true for the identical packing of Case 4. In Case 5 an analogous situation arises, where a minimum cell and a complete cell are both possible.

It proves that, for every one of the cases, the complete unit cell is a six-sided parallelopiped, each edge of which has a length of $2R$. These are illustrated in Figure 5, which shows the portions of the spheres involved (stippled areas) and discloses on the cell faces the trace of the enclosed void or "throat-plane" (white areas).[8] In this figure the viewpoint or orientation for each cell is identical with that for the sphere assemblage of the corresponding case in Figure 3. These cells range from the cube in Case 1 with all interfacial angles of 90° to the simple rhombohedron of Cases 3 and 6 with no interfacial angles of 90°. In each case, the complete cell contains parts[9] of eight adjacent spheres; and if these eight parts were appropriately rearranged, they would form exactly one complete sphere. In other words, each complete cell contains the equivalent of exactly one sphere; the remainder of the volume of the cell is void. The minimum cell of each of Cases 2, 4, and 5 contains the equivalent of one-half sphere. Each face of the complete unit cell contains one sector of each of four different great circles; the aggregate area of these four sectors equals one great circle; and the area of the throat-plane is the area of the parallelogram face *minus* πR^2.

[8] See definition of "throat-plane" on p. 808.

[9] The authors have failed to find an established geometrical name for this portion of a sphere bounded by three or more intersecting great circles and the sphere surface. It is like a pyramid except that it has a base that is curved instead of plane. For convenience, we shall call the form a "sphero-pyramid"; and since in the present examples three great circles are always involved, the form may be called a "trigonal spheropyramid."

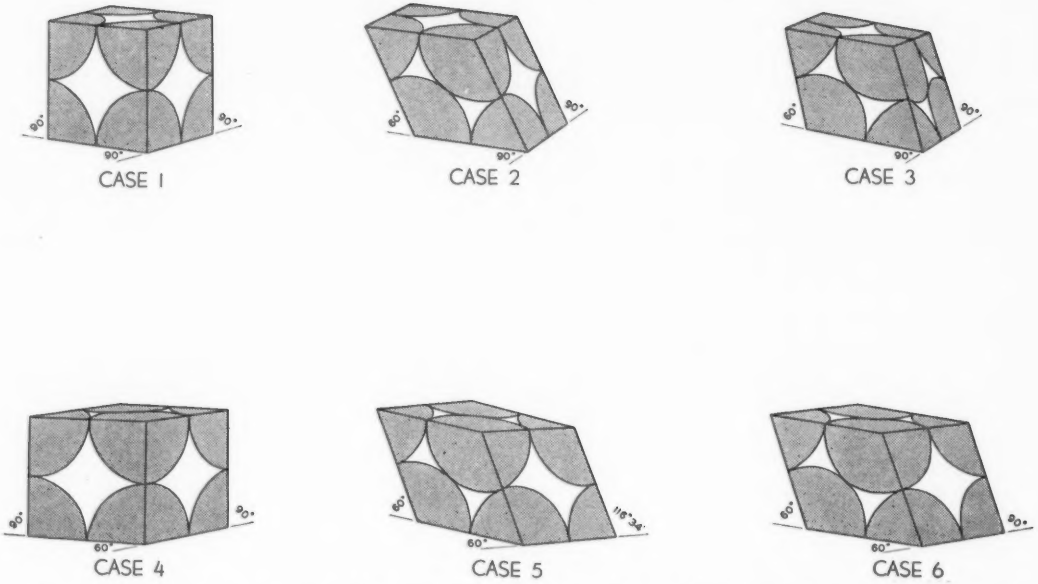


FIG. 5.—Unit cells of the six cases. The supplements of the face-angles are shown. Same orientations and scale as in Figure 3.

DESCRIPTION OF THE INDIVIDUAL PACKINGS

Case 1—cubic packing.[10]—In this type of packing, the "square layer" arrangement is present not only horizontally but as well in two vertical directions at right angles, so that three systems of square layers are present at angles of 90° to one another; they correspond to the cube faces. There are also present six identical systems of plane arrangement (not to be called "layers," as herein defined, because some of the rows are separated rather than contiguous or tangent); they are of rectangular pattern with sides respectively $2R$ and $2.83R$; and they pass through diagonally opposite edges of the cube, so that they have the same orientation to one another as do the faces of a rhombic dodecahedron. The unit cell of this scheme of packing is formed by passing three pairs of parallel planes through the sphere-centers located at the corners of a cube of edge $2R$; it has a volume of $8R^3$ and is shown under Case 1 in Figure 5. This is the only one of the six schemes of arrangement in

[10] There seems to be an unfortunate tendency in writings on the space-lattice to develop a terminology without regard, in all instances, to already established usages. This presumably can only lead to confusion. For example, the authors of an interesting paper entitled "The Structure of Topaz" (*Zeit. Krist.*, Vol. LXIX [1929]) show on their p. 164 diagrams illustrating two different types of closest packing; although both of these are based on the simple rhombic layer, they call one the "hexagonal" type and the other the "cubic" type. As a matter of fact, the first is a twinned *rhombohedral* packing of Case 6 which, because twinned, has lost the square layer and, therefore, lost some of its isometric characteristics (cf. herein p. 819); and their "cubic" packing is a normal rhombohedral packing of Case 6 with the square layer present in three sets of planes, and therefore possessing a considerable degree of isometric symmetry (cf. footnote herein on p. 802). But if this packing is to be called "cubic" packing, what is to become of the long-known "loosest" packing of Case 1, which is based directly on the cube? Still more disconcerting is the following concluding statement on p. 165 of the same paper:

". . . . there are an infinite number of ways in which an arrangement of atoms in closest packing can be formed by stacking in different sequence, one on top of the other, identical single layers of atoms in contact. The hexagonal and cubic types may be regarded as the simplest example of such stacking. . . . ."

The writers of the present article find no confirmation of the infinite number of ways of attaining truly "closest" packing (with a porosity of 25.95 per cent), and surmise that confusion in terminology has led to the erroneous conclusion. In order to avoid possible misunderstanding, we are avoiding the long-used "closest" packing (with a porosity of 25.95 per cent), and substitute for it the term "tightest" packing. See also W. P. Davey, *A Study of Crystal Structure and Its Applications* (New York, 1934), pp. 359–62.

which the simple rhombic layer is absent. It is, in fact, the "loosest" or the most open-textured packing that can be produced under the simple systematic conditions previously prescribed.

Case 2—orthorhombic packing.—Here, as in Case 1, the "square layer" arrangement is present in three planes; but in this case they lie at angles of 60° to one another. There is also present one plane or system of "simple rhombic layer" arrangement, lying at right angles to the three "square layer" planes. Also present is a plane rectangular pattern (not "layer") of sides $2R \times 3.46\ R$; this occurs in three planes or systems at 60° to each other and at 90° to the simple rhombic layer. The minimum cell is a trigonal[11] right pyramid all of whose edges are $2R$; the volume of this minimum cell is $3.46R^3$. The complete cell is a six-sided form, four of whose faces are squares of side $2R$ and two of whose faces are "simple" rhombs of side $2R$; the volume of such a cell is $6.93R^3$. (See Fig. 5.)

Case 3—rhombohedral packing.—The "square layer" arrangement is again present in three different planes at 90°, in this instance corresponding to the three diagonal planes of a regular octahedron. There are also present four planes or systems of "simple rhombic layer" arrangement, parallel to the respective faces of the octahedron (or of the tetrahedron). The unit cell is formed of six planes passed through eight sphere-centers situated at the corners of a regular or "simple" rhombohedron each of whose edges measures $2R$; the volume of this unit cell is $5.66R^3$. (See Fig. 5.) This is the "tightest" or most compact possible arrangement of solid spheres. This manner of packing may very appropriately be called rhombohedral, as Slichter[12] named it.[13]

[11] It is obvious that there are elements of hexagonal symmetry of a low order in this packing; indeed, if it were not for the factor of orientation, the case might properly be named "trigonal" instead of "orthorhombic."

[12] C. S. Slichter, *U.S. Geol. Surv. 19th Ann. Rept.*, Part II, (1899) pp. 306 ff.

[13] But while the hexagonal (rhombohedral) symmetry dominates, this form possesses strong isometric affiliations also. This is evidenced in part by the presence of three systems of the square layer arranged mutually at 90°. Indeed, in 1893, Lord Kelvin (*Proc. Roy. Soc. London*, Vol. LIV, p. 61), who called this manner of packing the "equilateral homogeneous assemblage," noted its *tetrahedral* characteristics. It is, moreover, the "face-centered cubic" arrangement of space-lattice terminology (cf. Bragg, *The Crystalline State* [1933], p. 144). And, as shown on p. 813, its complete unit cell may be

Case 4—orthorhombic packing.—In internal arrangement, this packing is identical with Case 2. If a body built by the stacking of square layers as in Case 2 is rotated 90° about the edge formed by the junction of the basal square layer with the simple rhombic layer, the attitude of the body in space will become that of Case 4. In Figure 5 the unit cell of this case is shown; it is the same cell as shown in the same figure for Case 2 but seen from a different angle corresponding to the different orientation in space.

Case 5—tetragonal-sphenoidal packing.—This type of packing has the "simple rhombic layer" present in two planes or systems at right angles. This is the only one of the six schemes of packing which possesses no "square layer" arrangement. But instead it possesses four planes or systems of a layer just off "square"; namely, a layer determined by a unit rhomb of side $2R$ and having face angles of 75°31′–104°29′ and diagonals with a ratio of 1:1.29 (instead of 1:1 for the square and 1:1.73 for the "simple" rhomb). These four planes have the same positions relative to one another as do the faces of a first-order tetragonal sphenoid; and with respect to such planes the two systems of simple rhombic layers are disposed as the faces of the tetragonal prism of the second order. There are also present two systems of rectangular pattern (not "layers" in the strict sense) of sides $2R$ and $2.45R$, lying at right angles to each other and parallel to the faces of a first-order tetragonal prism.

---

regarded as composed of two tetrahedra and an octahedron. Slichter briefly noted (*op. cit.*, p. 307) the presence of the three directions of "square layer," but made no reference to the propagation of this *cubic* element throughout the entire assemblage in rhombohedral packing and gave no evident recognition of the marked effect produced on porosity and permeability by the presence everywhere of this open-textured (square) component in so-called "tightest" packing. Kelvin, on the other hand, while clearly appreciating the factor of orientation, apparently failed, nevertheless, to recognize that the tetrahedron is not the complete unit cell of this packing, for while four spheres located at the respective corners of a tetrahedron give the essence of this scheme of "equilateral" or rhombohedral packing, as Kelvin pointed out, and while two such tetrahedral groups of four spheres each, when assembled base to base and one rotated 60° with respect to the other, will give the complete rhombohedral assembly, it is nevertheless true that the angular and distance relations between the spheres in each tetrahedral group are *not* identical with the relations of the spheres of one tetrahedral group to those of the other similar group. In short, the tetrahedron does not embody the complete expression of this rhombohedral packing. The surprisingly complex geometry of this tightest packing is more fully explained on pp. 810–15.

The sphenoidal or low-symmetry character of this arrangement gives it some analogies to the monoclinic system, but there is nothing in its makeup that violates tetragonal symmetry. The unit cell of this packing lies within six planes passed through eight sphere-centers located at the corners of a rhombohedron-like figure of which four faces are the "simple" rhomb of edge $2R$ and two faces are of the special rhomb described just above; the volume of this cell is $6R^3$ (see Fig. 5). As a matter of fact, this is double the minimum cell for this case, since, as in Cases 2 and 4, the essence of the packing—except for orientation—is given by a cell bounded by five planes as follows: one of "simple" rhombic shape of side $2R$, two of equilateral triangular shape of side $2R$, and two of the special rhomb already specified above. Such a minimum cell has a volume of $3R^3$.

Case 6—rhombohedral packing.—Internally, this packing is identical with that of Case 3; it therefore has the same unit cell. If the body built upon the square layer of Case 3 be rotated 109°28′ about an edge of the basal square layer, its various layers will take up the same attitude in space as that produced by building Case 6 on the simple rhombic layer. In Figure 5 is shown this unit cell in its proper orientation for this case; it is the same cell as is shown for Case 3 in the same figure but seen from a different angle.

GEOMETRY OF THE VOIDS

General Considerations

While porosity and permeability are determined, obviously, by the *voids* between the spheres as packed, attention in most earlier discussions of packing has been too much focused on the spheres themselves and too little concern has been given to the openings which the various modes of packing leave between the spheres. Not only has the treatment of the voids themselves been inadequate, but, because inadequate, it has permitted in some instances the entrance of outright errors. In the following discussion, the shape, volume, and arrangement of the intersphere voids are given specific consideration as they are determined by the several packings.

Each independent kind of packing is associated with a characteristic geometry of voids. In each type of packing, the ratio of the

total volume of the voids to the total volume of the body is the porosity for that particular mode of packing; this is the same ratio as that of the complete unit void[14] to the complete unit cell. Thus, for each of the different kinds of packing there is a given characteristic porosity, which of course holds constant regardless of the size of the unit sphere. Table II shows the volume of the unit cell, the volume of the unit void, and the porosity value in per cent for each of the several modes of packing.

TABLE II

POROSITIES OF THE VARIOUS PACKINGS

ARRANGEMENTS OF SQUARE LAYERS

	Case 1	Case 2	Case 3
Volume of unit cell*	$8.00R^3$	$6.93R^3$	$5.66R^3$
Volume of unit void*	$3.81R^3$	$2.74R^3$	$1.47R^3$†
Porosity	47.64%	39.54%	25.95%

ARRANGEMENTS OF SIMPLE RHOMBIC LAYERS

	Case 4	Case 5	Case 6
Volume of unit cell*	$6.93R^3$	$6.00R^3$	$5.66R^3$
Volume of unit void*	$2.74R^3$	$1.81R^3$	$1.47R^3$†
Porosity	39.54%	30.19%	25.95%

* The volume of the complete cell and of the corresponding void is given for each case. The volume of the unit void is in each case derived by subtracting the volume of the unit sphere, $4.19R^3$, from the volume of the unit cell.

† As shown on pp. 812–13, the void of Cases 3 and 6 is composite, and it is the volume of the composite void that is given here.

It will be noted that, just as the square layer is a looser or more open arrangement than the "simple" rhombic layer, so the packings built on the square layer are in general more open or of higher porosity than those built on the "simple" rhombic layer. It will further be seen, by reference to Table I, that, in general, as would be expected, the porosity decreases with decreased spacing of the layers and with increased number of tangent neighbors. As Dr. Peacock has suggested, it might be expected, also, that the porosity would vary in some orderly way with the degree of symmetry of the

[14] See definition on pp. 792 and 808.

several packings. But it becomes evident on inspection of the porosity percentages that such a relationship does not consistently hold; Case 1 has the highest porosity and it also obviously has the highest symmetry of any of the six cases, but corresponding condition does not prevail steadily as one passes to packings of progressively lower porosity. The reason for this failure of direct relationship between symmetry and porosity appears to be that symmetry, after all, is entirely determined by *angular* relationships and not primarily by *distances;* for example, spheres of radius R placed at the corners of a cube of edge $3R$ or $4R$ or any larger multiple of R would produce an assemblage having the same symmetry as if the cube had the edge of $2R$ (as in Case 1), but the porosity of assemblages built on the larger cubes would be greater than of that built on the smaller cube. Thus, porosity and symmetry cannot be expected to vary proportionally. The identity of the porosities of Cases 2 and 4 and of Cases 3 and 6 as shown in Table II is a consequence of the corresponding identity of these schemes of packing.

It has already been pointed out that the six simple schemes of packing herein considered are only special cases of an infinite variety of possible packings lying between the extremes of Case 1 and Case 6. Slichter has treated this situation by regarding the cube and the "simple" rhombohedron[15] as special limiting cases of a "general rhombohedron" capable, by variation of its face angles to any intermediate value between the 90° and the 60°–120° of these limiting cases, of representing the equivalent of every possible variety of systematic packing between the cubic, or loosest, and the rhombohedral, or tightest. He has then computed the porosities[16] for several of these intermediate rhombohedral arrangements; thus a rhombohedron whose voids represent a porosity of 30 per cent he finds to have face angles 62°36′–117°24′, and one with a 40 per cent porosity has face angles of 71°28′–108°32′. These examples of Slichter's may be contrasted with the closely similar porosities of 30.19 per cent and 39.54 per cent afforded, respectively, by Cases 5 and 2, in neither of which is the unit cell a true regular rhombohedron of equal faces.

[15] A rhombohedron each of whose faces is the "simple" rhomb of edge $2R$ already defined; it is the unit element or unit cell of Cases 3 and 6.

[16] Slichter, *op. cit.*, p. 312.

This conception of an infinite series of possible "intermediate" rhombohedrons, each with a given porosity, as entertained by Slichter, helps undoubtedly to emphasize the inescapable effect of packing on porosity. But it would seem that such intermediate rhombohedral arrangements are, in the first place, less likely actually to occur in a natural assemblage of solid units; moreover, they seem more arbitrary, less varied, and therefore less general, less easy of visualization, and less enlightening than are the six cases here presented, which are based on the simple geometrical relationships shown in Figure 2 and in Table I, and are analogous to well-known simple crystal forms; and finally, complete and exclusive commitment to this conception of a "general rhombohedron" leads to various real errors.[17] Therefore, Slichter's intermediate packings and his "general rhombohedron" will not be considered further in connection with porosity. The simplicity and symmetry of the six cases herein entertained becomes especially evident in connection with the analysis of permeability on later pages; on the other hand, the range of variation embraced by these six schemes is evidenced by the strikingly different shapes of the unit voids, now to be discussed.

The Unit Voids

The voids in a mass of material may be of two kinds: isolate or conjugate. The individual vesicles in an otherwise dense volcanic glass and the space occupied by the gas- or liquid-inclusions in a single crystal afford good examples of the isolate void. The intercommunicating and ramifying openings between the fragments of a

[17] For example, this conception provides only for unit cells (or "unit elements of volume," as Slichter called them) all of whose faces are identical. This not only contradicts the relationship shown for tightest rhombohedral packing in Slichter's Fig. 55, p. 307, where square and rhombohedral arrangements occur together, but also would exclude the very real and simple packings of Cases 2-and-4 and 5 here described. Undue adherence to this conception of a universal *rhombohedral* packing must also evidently be accountable for Slichter's assertion (*op. cit.*, p. 307) that if the spheres are not in tightest packing each will touch only *six* neighbors (cf. Cases 2 and 4 where eight neighbors, and Case 5 where ten neighbors actually touch); and may possibly be partly responsible for his repeated reference to the triangular or approximately triangular cross section of the ducts (or "pores," as he called them) that pass through the various assemblages and determine their permeability—whereas in fact, as shown hereafter, the triangle by no means typifies the cross section of these ducts.

talus heap or between the grains of unconsolidated sand are conjugate voids.

It is obvious that all the voids present in any assemblage of discrete or uncemented spheres must be of the interconnecting or conjugate type. The anastomotic or sponge-like composite void present in any considerable aggregation of spheres is therefore likely to be too complex for easy analysis. But such a composite entity may conveniently be visualized in its elemental units in consequence of the fact that the curvature of the sphere surfaces occasions alternate constrictions and enlargements of the intersphere openings; at the narrowest or most constricted places, which may be designated *throats*, imaginary transverse planes may be passed so that they will separate adjacent enlargements—these planes may be called *throat-planes;* and when each enlargement has thus been cut off by throat-planes from all its several immediately neighboring enlargements, we shall have produced what may be termed the *unit void.* In a chance aggregation of spheres, the unit voids are of variable shape, size, attitude, and distribution. But in simple systematic packing, of whatever particular type, the unit void is a three-dimensional shape bounded partly by (eight) spherical and partly by (six) plane surfaces. The orderly repetition of identical spheres brings about the orderly repetition of identical unit voids (or identical combinations of unit voids); and the (imaginary) throat-planes that separate the unit voids from one another have a fixed and simple geometrical relationship to themselves and to the body as a whole. For example, in systematic packing, the throat-planes invariably stand perpendicular to the sphere surfaces that limit them—i.e., if extended, the planes pass through the centers of these spheres and thus become continuous with the throat-planes for all other unit voids lying between spheres of the same pair of adjacent layers. Stated otherwise, planes passed through the centers of neighboring spheres are invariably throat-planes for the intersphere voids. These throat-planes bound not only the unit voids but the unit cells also; that is, as has already been stated on an earlier page, the unit void in systematic packing is the void contained within the unit cell.

The unit void, when considered as a geometrical entity, must obviously be closed in on all sides; that is to say, in every direction it must be limited either by the converging cuspoid surfaces of tangent spheres or by the converging walls of a throat and finally a throat-plane. It is therefore impossible to secure such a closed-in or surrounded unit void in a single layer of spheres; the spheres of two adjacent layers are required. It is for the same reason that the unit cell always includes parts of spheres of two layers.

In Figure 6 are shown the unit voids for each of the six cases; the graduated shading of the curved areas readily distinguishes them from the white or uniformly stippled throat-planes. The void for each case is shown in perspective from exactly the same angle of view and to the same scale as that for the corresponding unit cells of Figure 5 and the corresponding sphere assemblages of Figure 3. The voids shown in Figure 6, in other words, are what would be revealed if the portions of spheres (trigonal sphero-pyramids) shown in the unit cells of Figure 5 were removed, just as the unit cells shown in Figure 5 represent what would result from Figure 3 by passing planes through the adjacent sphere-centers and removing the outer portions of spheres so cut away.

The unit void of Case 1, lying between eight spheres in cubic arrangement, shows eight spherical triangular surfaces and six throat-plane surfaces that are concave-squares. It may be called a *concave-octahedron*. Its volume is 3.81 R^3, which is 47.64 per cent of the volume $8R^3$ of the cubic body that contains it.

In Case 2 and the identical Case 4, the unit void is bounded by eight spherical triangular surfaces, four concave-square throat-planes and two throat-planes each having the shape of two concave-triangles point to point. The void is shown in Figure 6, Case 4, oriented as if standing on the orthorhombic base, and in Fig. 6, Case 2, as if lying on one face of an orthorhombic unit prism. Its volume accounts for the 39.54 per cent porosity of this orthorhombic packing.

The unit void of tetragonal-sphenoidal packing, Case 5, is a peculiar double-wedge-shaped form bounded by four large and four small spherical triangles, two concave-rectangle throat-planes, and four throat-planes of the double-concave-triangle shape. Its volume

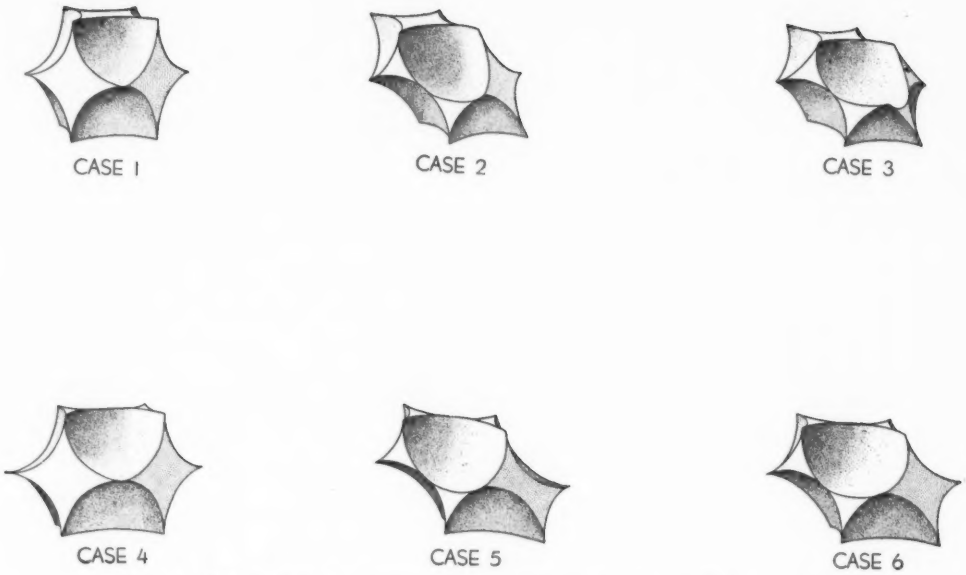


FIG. 6.—Unit voids of the six cases. Same orientation and scale as in Figures 3 and 5

accounts for the 30.19 per cent porosity of tetragonal-sphenoidal packing.

The unit void of Case 6 presents rather unexpected complexity. The simplest and the smallest void that can be formed among uniform spheres is that lying between four spheres in tetrahedral arrangement. Such a void is bounded by four concave-spherical surfaces having the shape of spherical triangles and by four throat-planes of concave-triangular outline. Collectively, these eight bounding surfaces have the angular relationships suggestive of an octahedron. But since the spherical surfaces are the dominant ones while the throat-planes are incidental, this type of void may be conveniently designated a *concave-tetrahedron;* this name is suggestive also of its four bounding spheres. A true regular tetrahedron formed by passing planes through the centers of the four spheres so involved has a volume of approximately $0.94R^3$; the portions of the four spheres included in such a tetrahedron have an aggregate volume of approximately $0.73R^3$. Therefore the void in this tetrahedron has a volume of about $0.21R^3$, and represents a porosity for the tetrahedral body of 22.00 per cent.

Now, since the building-up of such a tetrahedral arrangement of four spheres starts with three spheres of one layer in the simple rhombic arrangement and in the second layer a fourth sphere placed in the three-sided hopper between the other three, this arrangement would appear to be identical with that by which Case 6 is produced (cf. Fig. 2). Therefore, one would, at first thought, conclude that the unit void of Case 6 would be the concave-tetrahedron just described and that the porosity in Case 6 would be the tetrahedral porosity of 22.00 per cent just mentioned. But one here comes upon a somewhat unexpected relationship. If one looks down upon a layer of spheres in the simple rhombic arrangement (see Fig. 7), one sees the three-sided hopper lying between each three spheres in equilateral-triangular arrangement, and the eye instinctively conveys the expectation that if a sphere be placed in each such hopper, the second layer of spheres will be thus filled out. But one finds that it is impossible (because there is not enough room) to place spheres of the second layer in *every* such first-layer hopper; each alternate

hopper must be left empty. Those hoppers of the first layer marked "1" in Figure 7 can be occupied by spheres of the second layer, but thereby the hoppers marked "2" will be so covered that spheres will not fit into them and they must be skipped; when spheres are put into the hoppers marked "3," these spheres will just fit (in simple rhombic arrangement) with those occupying the "1" hoppers and the empty "2" hoppers will then be completely surrounded. As a matter of fact, in a layer of simple rhombic arrangement, there are

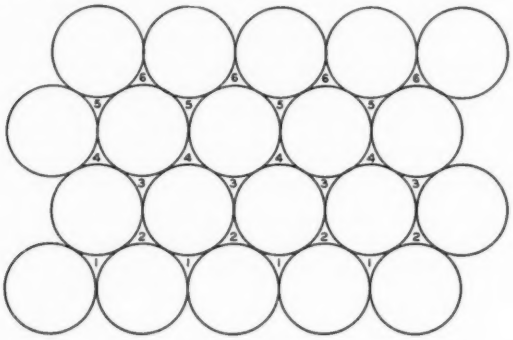


FIG. 7.—Space relations of the simple rhombic layer

twice as many hoppers as spheres, therefore only half these hoppers (each alternate one) can be occupied by spheres of the next-overlying layer.[18]

When each hopper that has had to be left unoccupied becomes fully surrounded by three spheres of the second layer, it becomes a closed-in void, but proves to have larger size and different shape from the concave-tetrahedron discussed shortly above. As a matter of fact, it is a void bounded by parts of six spheres lying at the corners of an octahedron and by eight throat-planes of concave-triangular shape and coincident with the octahedron faces; the six dominant curved surfaces of this void are so arranged as to justify for it the name *concave-cube*. It has a volume of about $1.05R^3$, or

[18] That is, if all the odd-numbered hoppers of Fig. 7 are occupied, all the even-numbered hoppers will remain empty; and, similarly, if the even-numbered are occupied, there will be no chance to fill the odd-numbered.

slightly more than five times that of the concave-tetrahedron void; and with respect to its containing octahedral cell (which has a volume of $3.77R^3$), it represents a porosity of 27.93 per cent.

In short, although Case 6 might seem to be the simplest, as well as the "tightest," mode of packing, it is in a sense the most complex, for it actually contains two kinds of voids: the concave-tetrahedron and the concave-cube. That this must be true is shown by the fact that in the identical packing of Case 3, built by starting with the square layer, four-sided hoppers are present; these, when closed in by the second layer, become the concave-cube voids, while alternating between these are voids of the concave-tetrahedron shape. It proves that, in both Case 3 and Case 6, for each concave-cube void there are two concave-tetrahedron voids. These relationships are presented in Figure 8, where *B* shows the unit cell of Case 6 (when assembled according to the arrangement indicated in *A*[19]) and *D* shows the corresponding unit void. In *C* of Figure 8 the unit cell is shown separated into two tetrahedra and an octahedron, and in *E* are shown the corresponding concave-tetrahedra and the concave-cube which collectively are equivalent to the full unit void shown in *D*. The concave-cube of *E* is the void element that occupies the alternate unfilled three-sided hoppers of Case 6 and occupies the square hoppers of Case 3. In *C* and *E* of Figure 8, the oblique parallel

[19] Comparison of Fig. 8, *B*, with Case 6 of Fig. 5 indicates that the two unit cells are not identical. This difference does not arise from mere difference in angle from which they are viewed (as is true for the apparent difference between Case 3 and Case 6 in Fig. 5), for these are actually different cells. But each is equally expressive of rhombohedral packing. The difference between the two cells is this: The sphere assemblage of Case 6 as shown in Fig. 3 is built by such stacking of the second layer on the first as puts each sphere of the second layer obliquely upward *to the "northwest"* from the corresponding sphere of the first layer, and the unit cell shown for Case 6 in Fig. 5 corresponds to that arrangement; on the other hand, the unit cell of Fig. 8, *B*, corresponds to a sphere assemblage built by such stacking as puts each sphere of the second layer obliquely upward *to the "southwest"* from the corresponding sphere of the first layer. This difference may be graphically seen by comparing the top-view key to arrangement of Case 6 in Figure 1, *B*, with that in Fig. 8, *A*. Actually, different unit cells result. The cell of Case 6 in Fig. 5 contains two concave-tetrahedrons, the half of one concave-cube and the half of another concave-cube; the cell of Case 6 in Fig. 8, *B*, contains two concave-tetrahedrons and a single whole concave-cube. But both cells come from identically the same packing. The unit cell and the unit void illustrated by Slichter (*op. cit.*, pp. 309 and 310) correspond exactly to those shown here in Figs. 8, *B*, and 8, *D*, respectively.

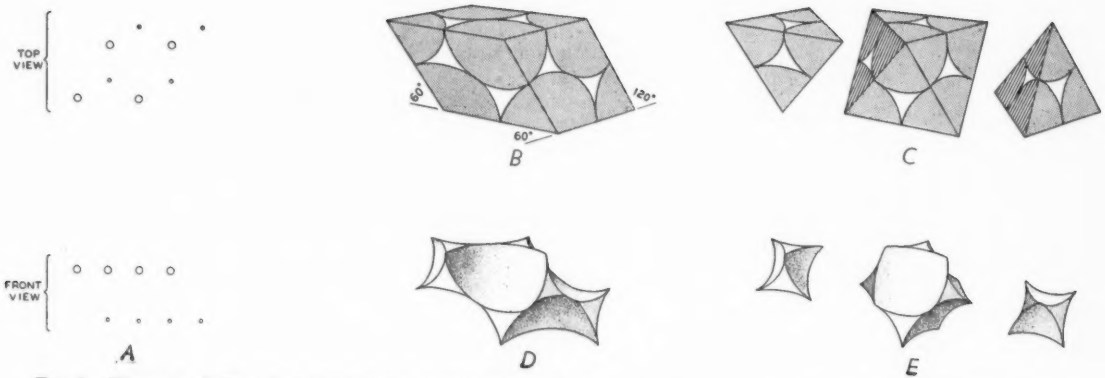


FIG. 8.—Elements of the unit cell and the unit void of Case 6. *A*, key to arrangement; *B*, unit cell; *C*, elements of unit cell; *D*, unit void; *E*, elements of unit void. Same scale as in Figure 3.

hatching indicates the planes along which the unit cell of *B* and the unit void of *D* have been cut and separated into their elements.

The value 25.95 per cent given as the porosity of "tightest" packing of Case 3 and 6 is thus, in fact, a weighted average of the porosity of 22.00 per cent in the two tetrahedral elements and of 27.93 per cent in the octahedral element, which three elements collectively make up the complete rhombohedral unit cell. Each of the two concave-tetrahedron voids accounts for 3.68 per cent and the concave-cube for the balance, or 18.58 per cent of the total of 25.95 per cent porosity of this rhombohedral packing.[20]

This composite nature of voids in "tightest" packing is of especial importance in connection with the factor of permeability as discussed later; and failure, apparently, to recognize this composite character in earlier discussions of the geometry of permeability may account for some of the errors that have crept therein.

TWINNED AND TRIPLED PACKINGS

By reference to Figure 2, it will be seen that in Cases 1, 3, and 4, no other manner of stacking the successive layers is possible than that indicated, if the conditions stipulated in Table I are to be met. But in the other three cases, alternative stackings are possible while still adhering to the conditions imposed. In Case 2, for example, the second layer may be offset to the right with respect to the first layer, as is shown in Figure 2, or it could equally well be offset away from the observer. These alternatives are better shown in Figure 9, *A*, where the projections of the four spheres typical of the first or basal layer are shown in faint circles and are numbered, and the corresponding projection of the No. 1 sphere for the second layer is shown with heavy circle; the relation of the No. 1 faint circle to the heavy circle gives the key to the manner of stacking the layers. Figure 9, *A*, shows the two alternative methods, *I* and *II*, of stacking in Case 2. Figure 9, *B*, shows, analogously, the two alternatives possible in Case 6; and Fig. 9, *C*, shows the three alternative ways of stacking the layers of Case 5.

[20] Stated in another way, the concave-cube void accounts for 71.60 per cent of the total porosity of "tightest" packing, and the two concave-tetrahedrons account for 28.40 per cent, or 14.20 per cent each.

Now, in Case 2, for example, systematic stacking of layers always in accord with alternative *I* will give the same identical internal packing[21] as by stacking always in accord with alternative *II*. But if the second layer is stacked on the first layer with the offset according to alternative *I*, and the third layer stacked on the second with the offset according to alternative *II*, and this offsetting first one

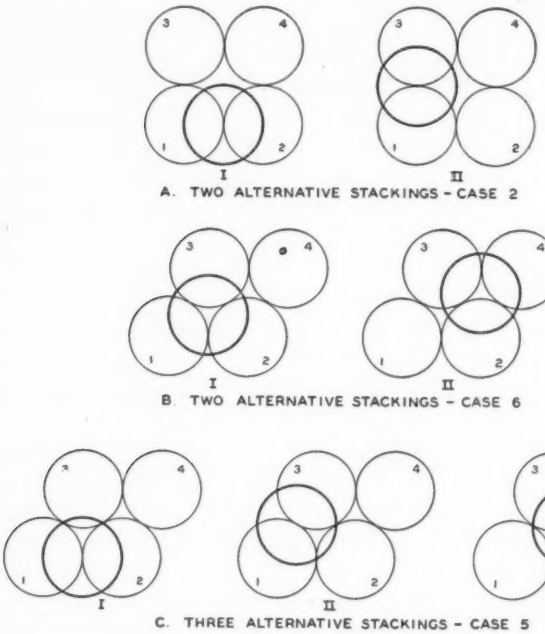


FIG. 9.—Alternative methods of stacking

way and then the other is systematically repeated, then an actually different packing will result. Under such circumstances, the voids between the first and second layers, the third and fourth layers, etc., will be oriented identically; but the voids between the second and third layers, the fourth and fifth layers, etc., will be rotated

[21] The orientation in space, however, of the resulting body or assemblage will differ: that in the one case will be rotated in space 90° in the plane of the base with respect to that in the other body.

90° in the horizontal plane with respect to the voids first mentioned. Except for this difference in orientation, however, all the voids are identical. Such systematic and repetitive alternation of stacking produces a packing and a structure entirely analogous to multiple twinning in crystallography; and the packing thus resulting may therefore properly be designated a *twinned packing*. Since no change in number, shape, or size of the voids results form the twinning, the porosity of the twinned packing is identical with that of the normal or untwinned packing of Case 2; but, as will later be seen, twinning has a marked effect on permeability.

The key to the twinning in Case 2 is shown in Figure 10, *A*, where the position of each tiny circle represents the downward-projected position of the center of the No. 1 sphere for the layer whose number is indicated; thus circle 1 represents the position of a given sphere of the first layer, circle 2 represents the projected position of the corresponding sphere of the second layer, circle 3 of the third layer, etc. The two alternative ways, *I* and *II*, of untwinned stacking are there indicated, and also the twinned stacking that results from stacking first according to *I*, then according to *II*, then according to *I* again, and so on. Similarly in Figure 10, *B*, are shown the two untwinned stackings and the one twinned stacking of Case 6. And in Figure 10, *C*, are shown the key to three untwinned packings—the two options of twinned packing and the one tripled packing of Case 5.

It is noteworthy that although Case 2 and Case 4 give identical normal or untwinned packings, Case 2 permits twinning while Case 4 does not; that is to say, Case 4 cannot be produced in a twinned arrangement by the stacking of *plane layers*, which are the conventional elements of stacking adopted in the present paper. The explanation is that, although the normal packing of Case 2 contains the simple rhombic layer upon which Case 4 is built, the twinned arrangement of Case 2 breaks up the simple rhombic layer into a series of staggered offsets or steps. Similarly, although Case 3 and Case 6 give identical normal packings, Case 6 permits twinning, but Case 3 does not. The reason is analogous to the previous instance: while the normal packing of Case 6 contains the square layer upon which Case 3 is built, the twinned arrangement of Case 6 breaks

up the square layer. From this standpoint of twinning, therefore, there is a difference between Cases 2 and 4 and between Cases 3 and 6, occasioned by their respective differences in space-orientation; it is for this reason, as earlier noted, that the discussion has been con-

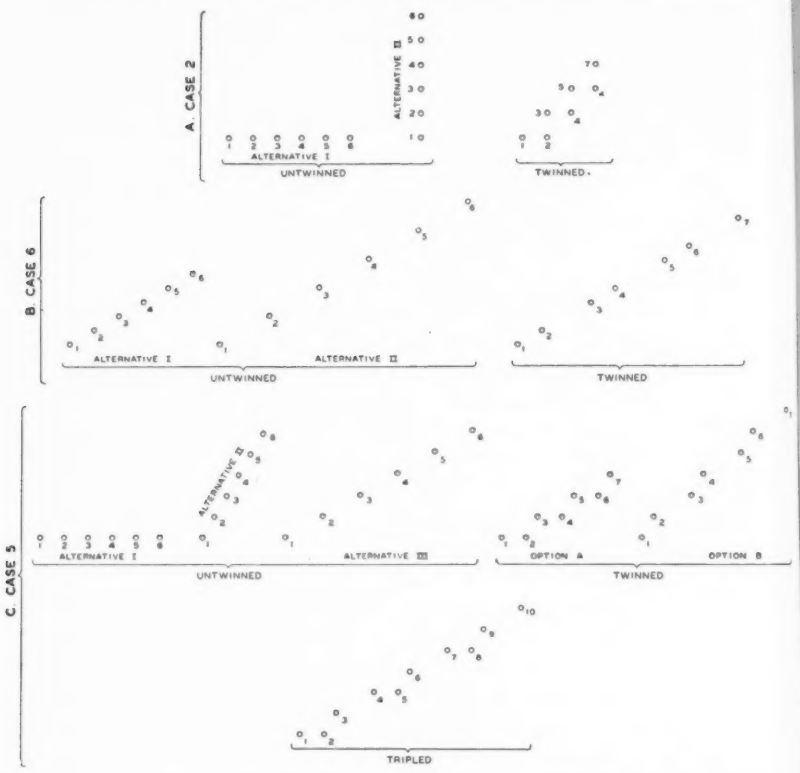


FIG. 10.—Key to untwinned, twinned, and tripled packings

sistently carried through on the basis of all six cases of packing, instead of combining Cases 2 and 4 and Cases 3 and 6 and thus treating only four packings.

It is the presence of *two* alternative ways of untwinned stacking in Case 2 and in Case 6 that permits the one manner of twinned

packing in each of those cases; it is the presence of *three* alternative ways of untwinned stacking in Case 5 that gives two different ways of twinned stacking and one[22] way of tripled stacking in that case.

It is obvious that these alternatives involving twinned or tripled packing may be adopted rhythmically and systematically, or, on the contrary, quite erratically. Only the very simplest systematic examples have been considered in the preceding paragraphs. With an option as between alternative *I* and alternative *II*, there is probably no more reason why the selection in natural stacking must always be in the order *I*, *II*, *I*, *II*, *I*, *II*, than why it must always be *I*, *I*, *I*. Therefore, it may be wholly natural for the stacking to involve such chance order as *I*, *II*, *II*, *I*, *II*, *II*, *II*, *I*, *I*, etc. But in this matter, as in all other phases of the present geometrical analysis, it is only the more simple or the limiting cases that can be advantageously considered in any detail. Systematic twinning would, of course, result if the options were alternated every second layer, or every third layer, etc.; but the very simplest arrangement would be alternation with *every* layer, and the only systematic twinnings that are entertained in this paper involve that simplest condition. In Figure 11 are illustrated, as samples of such twinning and tripling, the skeleton outlines of a multiple-twinned unit cell of Case 2 and of a multiple-tripled unit cell of Case 5; the heavy lines designate the twinning planes, and the Roman numeral on each layer indicates, by reference to Figures 9 and 10, the particular alternative manner of stacking adopted for that layer with respect to the layer below.

It is again to be emphasized that, regardless of whether the various alternations that result in twinning are selected rhythmically or irregularly, the *porosity* remains constant. The question, therefore, naturally arises as to why there is anything to be gained in this consideration of twinned and tripled packings if they have no effect upon the porosity. The answer is that, while the number and shape of the voids is not changed by twinning or tripling, their angular relation to one another in space is very definitely altered; and this has an

[22] Stacking in accordance with the order *I*, *II*, *III*, *I*, *II*, *III*, etc., gives exactly the same tripled packing internally as if the order adopted were *I*, *III*, *II*, *I*, *III*, *II*, or were *III*, *II*, *I*, *III*, *II*, *I*.

influence on the stability of the body, as shown just below, and it also has an important effect upon the permeability of the body, as will be graphically seen from subsequent illustrations.

RELATIVE STABILITY OF THE VARIOUS PACKINGS

It is evident that in some of the packings complete stability of arrangement is inherent in the manner of stacking, while in others a lower degree of stability is attained. Any solid mass (e.g., a

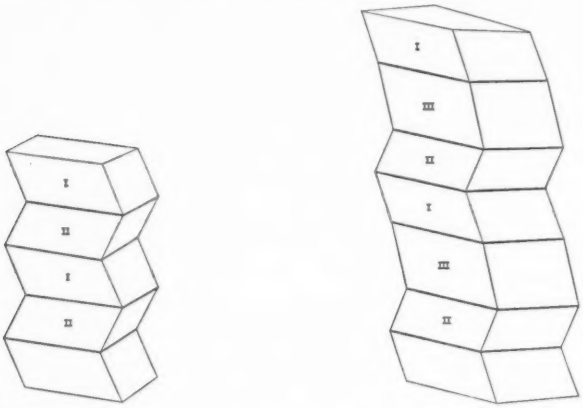


FIG. 11.—Examples of twinned and tripled packings. Orientation of lowest layer of *A* as in Figure 5, Case 2. Orientation of lowest layer of *B* as in Figure 5, Case 5. The thickness of all the layers is equal; the apparent disparity in thickness is due to the different degrees of fore-shortening on the planes lying at different angles to the line of sight.

sphere) acted upon by gravity and supported from below requires at least three points of support in order to attain equilibrium, i.e., acquire a fixed and stable position. When this requirement is applied to spheres in an assemblage, it is found that of the six schemes of packing here entertained, only Cases 3 and 6 are completely stable arrangements (cf. Fig. 2), since only in these two cases do the individual spheres of any layer have three or more points of supporting contact with the spheres of the layer next below (four such points of support in Case 3 and three in Case 6).

In Cases 2 and 5, each sphere receives support from the underlying layer at only two points; with respect to this underlying layer, each sphere is thus "balanced" in the cusp between the two underlying spheres, and except for lateral support afforded by its neighbors in its own layer (which may themselves be no better supported) it can be very easily toppled, to one side or the other of the plane of this cusp, thus falling or rolling down into the nearest hopper-like depression of the underlying layer, whereupon it acquires adequate support but, in so doing, changes the packing from Case 2 to Case 3 in the one instance and from Case 5 to Case 6 in the other instance. Cases 2 and 5 may therefore be regarded as possessing partial but

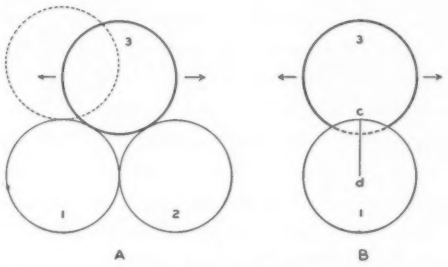


FIG. 12.—Stability relations in "balanced" packings

not complete stability: such packings can easily be toppled in one direction or its opposite (i.e., to either side of the plane of the cusp in which each sphere rests) (see Fig. 12, *B*) but are stable with respect to lateral impulses acting in the plane of the cusp (see Fig. 12, *A*).

In Cases 1 and 4 each sphere is perched even more precariously on the very pinnacle of a single underlying sphere; therefore these packings are still more acutely unstable except as they acquire some fixity and stability through support afforded by their lateral neighbors. When such a perched sphere of Case 1 or Case 4 topples and rolls down on the curved surface of the underlying sphere, it is most likely to roll all the way down into one of the adjacent hoppers that surround the underlying sphere; the toppled sphere thus reaches a position of complete support and stability, but the packing thereby

changes from Case 1 to Case 3 in the one instance or from Case 4 to Case 6 in the other instance. But if, in the course of thus rolling downhill, the toppled sphere falls in any one of four special directions (spaced successively at 90°) in Case 1, or in any one of six special directions (spaced successively at 60°) in Case 4, it will find at least a temporary resting-place of partial stability (i.e., two-point support) in the cusp between the sphere down which it is rolling and the adjacent neighbor of the latter (see Fig. 12, *A*); if each sphere of a given layer of Case 1 were to topple in the same one of these four alternative directions and come to rest in such a cusp, Case 2 packing would result; and if each sphere of a given layer of Case 4 were to topple in the same one of these six alternative directions and come to rest in the appropriate cusp, Case 5 packing would result.

It is thus seen that Case 2 and Case 5 are, respectively, special intermediate packings of partial stability that may be produced in the course of the translation from the unstable Case 1 to the stable Case 3 in the one instance and from the unstable Case 4 to the stable Case 6 in the other instance. These intermediate Cases 2 and 5, while admittedly highly special, have a degree, even if a limited degree, of stability which the "general rhombohedral" arrangement visualized by Slichter would not possess at all. His "general rhombohedron" is, as it were, only a *snapshot* of the spheres at the positions they hold at some instant in the act of rolling down from the one extreme of Case 1 (cubic) packing to the other extreme of Case 3 (rhombohedral) packing; successive such snapshots would represent various of the infinite possible examples of the "general rhombohedron" as the face-angle changes between the limiting values from 90° to 60°; and there would be no quality of stability (not even the precarious perching of Case 1) in any of these general intermediate positions—save in those special instances of partial stability (support in cusps) that constitute Case 2 and Case 5.

In all these cases of unstable or partially stable packing, a given sphere located in the midst of its own layer receives from neighboring spheres in the layer a semblance and quality of support, and in its turn reciprocates the same manner of support to these neighbors; but this mutual "support" is of a spurious kind, and unless at

the eventual margins of the layer there is some fixed and stable limit or container wall, there will be everywhere (except in the bottommost layer) a tendency to topple, and therefore no true stability to the body.

There are other ways of expressing the relative stability of the various packings besides this mere consideration of the tendency to topple. For instance, a lone sphere in a given layer (except the first layer) of Case 1 may start to topple in *any* direction from its perched position and will roll down a considerable distance before coming to stable rest in any one of the four equally near hoppers of the underlying layer. A similar lone sphere in a given layer of Case 4, although likewise perched on a pinnacle and capable of toppling in any direction, will roll down *less far* before finding complete support and will have *six* equally near hoppers from which to choose its final position of stable support; moreover, the lateral stability afforded by the four-point contact in the horizontal square layer of Case 1 is less than the lateral stability contributed by six-point contact in the horizontal simple rhombic layer of Case 4. For these reasons, therefore, the stability of Case 4 is higher than that of Case 1. By corresponding analysis it will be found that the stability of the various packings[23] increases in the following order: Case 1, Case 4, Case 2, Case 5, Case 6, Case 3.

Still other ways of indicating or measuring the relative stabilities of the several packings are these: Of any two packings, that one is the more stable

a) Which has the lower porosity, and therefore the smaller volume and the higher density;
b) In which each sphere touches the larger number of neighbors;
c) In which a larger number of the tangent neighbors are in the underlying layer;
d) Which (for a given number of spheres) has, as a body, the lower center of gravity; i.e., the vertical spacing between layers is less;
e) In which each sphere occupies a position having lesser potential energy, and thus the potential energy of the body as a whole is less.

[23] For discussion of the stability of haphazard packing, see pp. 842–43.

The interdependence of these various factors is too obvious to need elaboration. But the reasons why identical packings, e.g., Cases 2 and 4, and Cases 3 and 6, have different stabilities need a word of explanation. With respect to Cases 2 and 4, reference to Table I shows that the spacing between layers is greater for Case 4 than for Case 2. Therefore, although these two Cases are on an equal footing with respect to the factors porosity and number of tangent neighbors, the arrangement in Case 2 has two of these tangent neighbors in the underlying layer (as against only one in Case 4), it yields a lower center of gravity, and its spheres have a smaller potential energy than the arrangement of Case 4. The greater stability of Case 2 than of Case 4, as already cited, is thus confirmed. For the same basic reasons, i.e., (*c*), (*d*) and (*e*) of the foregoing list, Case 3 is more stable than the identical packing differently oriented in Case 6.[24]

When a packing of one degree of stability is subjected to jarring or to jigging, there is a tendency for it to change or translate into some packing of higher degree of stability. If the lateral support is adequate, this tendency is nullified. But the lateral support acts not only to prevent each individual from toppling and rolling downhill—it operates to the same end also in another way, as follows: Attainment of a more stable packing means attainment of a lower center of gravity of the body, and this can be achieved only by a decrease in height and an appropriate increase in lateral dimensions of the body; adequate support from the sides prevents this lateral spreading of the body and therefore maintains the initial packing, no matter how unstable it may otherwise have been. Obviously, the degree of rigidity and adequacy of the lateral support will determine the extent to which the tendency of the body to "settle" into a closer, more stable packing will find realization.

With respect to Cases 3 and 6, the facts that Case 3 is of higher stability than Case 6 and that a packing of lower stability tends to translate into one of higher stability should imply that Case 6

[24] This difference of stability of the same packing in different orientations may be likened to the difference in stability of a box, depending on whether it is laid on its broad side or stood on its small end.

should try to become reoriented by internal readjustment into Case 3. But in this particular pair of cases, an additional factor discourages such translation besides the factor of lateral support already mentioned. In Case 6 as well as in Case 3, each sphere is already "stably fixed" in position by at least three-point support in a hopper of the underlying layer. In order that the orientation of Case 6 may change so as to attain the lower center of gravity and the four-point support from below that characterize the more stable Case 3, it would be necessary for the assemblage to pass through intermediate arrangements of greater porosity than the common least porosity of Cases 3 and 6; this would require a temporary *lifting* of each sphere from the Case 6 hopper in which it lay, and a temporary raising of the center of gravity of the body as a whole—this certainly would not result from a simple jarring wherein the downward pull of gravity is the maximum force acting, and it would probably only rarely happen as a consequence of jigging (alternate up and down forces), namely, when the amplitude of the jigging is exactly right to bring about this special outcome and not instead embarrass the whole scheme by causing local regions of disordered packing.

The probability of translation of Case 6 into the more stable orientation but identical packing of Case 3 therefore seems slight. Since, as will later appear, stacking is more likely to start on the simple rhombic than on the square layer as a base, Case 6 is more likely to form initially than is Case 3; and, when formed it seems probable that, although inherently less stable than Case 3, Case 6 will remain permanent, save under strong deforming forces or under just the right rhythm and intensity of jigging.

The effect of twinning or tripling is, in Cases 2 and 5, to increase the stability of the resulting assemblage. It will be recalled (see Fig. 12) that the stability of these two cases is low with respect to any disturbing impetus *across* the plane of the supporting cusp in which each sphere lies, while the stability is high with respect to impetus in the plane of the cusp. Twinning in these two cases brings about change from layer to layer in the orientation of the supporting cusps; and this has the effect of "locking" the spheres

in place and thus stiffening[25] the entire structure. This increased degree of stability comes by the addition of steadying from the layer above to the support from the layer below; but the gain in stability thus attained is not equal to that afforded by complete hopper support from below, as in Cases 3 and 6. Obviously, the increased stability due to twinning is greatest when *every* layer boundary is a twinning plane, and decreases as the interval between twinning planes widens. The twinning in Case 2 with 90° rotation is more effective in imparting stability than that in Case 5, where the rotation is 60°. Twinning in Case 6 produces no steadying not already present, and therefore no increase in the already high degree of stability.

It is to be noted that this entire discussion of stability is postulated on the assumptions that the downward pull of gravity is the only force of consequential importance at work on the system after the assemblage has been initially attained, and that the body remains (as a unit) untilted from the attitude it assumed when horizontal layers were piled to produce it. Lateral transporting or deforming forces, of any appreciable magnitude, or tilting of the base upon which the body rests, could bring about important modifications of stability relationships.

It is the difference in stability of different packings (whether systematic or otherwise) and the consequent tendency toward translation from a less stable to a more stable and less porous packing that give rise to the important and interesting phenomenon of dilatation[26] as exemplified in sands, slimes, and other similar assemblages.

The indicated great instability in the packings of Cases 2 and 5

[25] The situation may be likened to the piling of round sticks of firewood: it is impossible to build up a pile with vertical ends if the sticks are all laid parallel; but if at the ends an alternately crisscross arrangement or cobwork is built, a stable rectangular pile can be formed. Such alternate crisscrossing corresponds to twinning.

[26] Cf. W. J. Mead, "The Geologic Rôle of Dilatency," *Jour. Geol.*, Vol. XXXIII (1925), pp. 685–98. It may be noted here in passing that the customary definition of "dilatation" as that class of strain which involves volume changes but no angular deformation does not, after all, strictly apply to these translations from one packing to another packing of particles or grains, for, whenever such translation involves a change of volume for the body so affected, there is also a change in the angular relations between the grains.

and the even greater instability in those of Cases 1 and 4, and the related fact that when these sensitively perched or balanced packings topple they invariably *tend* to translate into the one really stable rhombohedral packing of Case 3 or 6, collectively afford some measure of justification for Slichter's virtual confinement of consideration to the "tightest" rhombohedral packing and for his development of a theory of permeability based directly on that simplest rhombohedral arrangement. But such extreme limitation and simplification of arrangement is not vindicated by natural packings. Instead, there is adequate justification for giving consideration to each of the four independent modes (six cases) of simple systematic packing treated in this paper.

But in addition, there are, of course, various other schemes of arrangement which, while yet geometrically systematic and orderly, are more arbitrary and less simple than the six cases principally treated herein. The most readily visualized examples are arrangements in which the angle and spacing of the sphere-centers differ in some systematic manner and degree from the angle and spacing in the six simplest cases. Among such are those instances typified by the "general rhombohedron" of Slichter. Furthermore, there are those countless varieties of assembly in which no orderly or systematic repetitive arrangement can be discovered; all these may be grouped together under the general term *chaotic* packing. All packings that do not correspond exactly to some one or other of the six simple systematic cases are here arbitrarily classed together as *haphazard* packing; since in these packings there may be present lower degrees or more complicated kinds of orderliness than characterize the six simple cases, they cannot be grouped as a whole under such a term as disorderly or chaotic packings; nevertheless, disorderly arrangement generally dominates in haphazard packing. The stability of haphazard packing is more effectively discussed later (see pp. 842–43). Finally, a given considerable assemblage of spheres is likely to vary from place to place as to manner of arrangement of the spheres—at certain places one of the six simple cases may be developed, at other places another case, while elsewhere various phases of haphazard arrangement exist, some of them entirely chaotic while others show some degree of orderliness. Any such as-

semblage which is not arranged throughout according to a single one of the six simple cases will be designated herein as *chance* packing. The stability of chance packing is the resultant of the stability of each of its component varieties of packing.

In any sphere assemblage, that portion which is arranged according to some one of the six simple cases is called a *colony* of that case. The minimum colony embraces the eight spheres necessary to enclose the unit void; but there is no maximum limit, since the entire assemblage—no matter how large—may consist of a single colony. Most commonly, however, the average natural aggregation or assemblage is composite, containing one or more colonies separated or surrounded by regions of haphazard packing; when more than one colony is present, all the colonies may represent a single case or, on the other hand, more than one case may be represented. There is a tendency for a given colony to be of compact chunky shape and more nearly equidimensional than strikingly long or thin; this probably is an expression of the magnitude of the tendency for a given simple case of packing to continue growing upward once it gets started.

PROBABILITY FACTORS FOR THE VARIOUS PACKINGS

Building of the Layer

Under the ideal conditions postulated in the present geometrical analysis, the chance that a given case of packing will be initially produced, instead of any of the other cases, will depend on a variety of factors. One of the most obvious and important of these factors is the relative stability of packing of that particular case. Other things being equal, that case is most likely to result which has the highest degree of stability. As shown in the preceding section, this would point to Case 3 as the most probable packing to be formed. But the question of stability of the completed body concerns primarily the manner in which the layers are stacked upon one another; or, stated in another way, stability is more concerned with the vertical than with the horizontal relationships between the spheres. If adequate enlightenment is to be had regarding the horizontal relationships, it is therefore necessary to inquire beyond the limits that relate to stability by examining the manner of forming the layer and

the relative chances of formation of the square layer and of the simple rhombic layer.

It may first be assumed that the accumulation of spheres is always initiated on a horizontal plane starting surface. Spheres brought to that surface and accumulating upon it as a first layer may come to rest either in positions of mutual contact or (at least for a time) in separated positions without contact. For the present, attention will be directed to the first of these alternatives, since only through mutual contact of spheres can be attained the ideal row and the ideal layer with which we have hitherto been dealing. Later, the second alternative will be considered.

Any two uniform spheres lying in mutual contact but aloof from others upon the horizontal starting surface afford two similar cuspate bays or re-entrants that determine two special positions along an otherwise monotonous convex "shore line" of the pair. A third sphere, transported along the starting plane into contact with the pair, is more likely to come to rest in one of the bays where it contacts with both spheres of the pair than at some chance place along the convex shore line where it contacts with only one; for with but one point of contact, its retention of that position is unlikely—the slightest recurrent impulse of the transporting force which brought it will tend to push or roll it along from this single-point contact until either it deserts the pair or it gets into one of the bays and becomes tangent to both of the two earlier spheres, in which latter position it takes on a quality of relative fixity. The placing of the third sphere in one of the cuspoid bays formed by the first two spheres now produces a 60° equilateral arrangement, and thus at once is determined the essential pattern of the simple rhombic layer; such placing also increases from two to three the number of re-entrant bays available for the reception of additional spheres. Each such succeeding sphere brought to this group upon the starting plane has the same greater tendency to take up its place in one of the bays than to make contact with only one of its predecessors. As the group thus increases, some of the new-coming spheres may come into contact not only with two but with three or even four of the spheres already assembled in 60° arrangement; also, as the group grows, the number of bays increases so that the chance of acquiring

additional spheres in this orderly arrangement becomes steadily greater.

It thus results that in the accumulation of spheres on a horizontal starting plane, there is a strong tendency to produce an orderly layer of the simple rhombic pattern. Moreover, the fact that in such an arrangement each interior sphere is "locked," as it were, in the six embayments between six neighbors gives to this layer a quality of steadiness that tends to preserve and perpetuate this pattern. As contrasted with the production of the first layer in this simple rhombic pattern, the likelihood that a square layer or any general rhombic placing other than the 60° or "simple" rhombic pattern would either get started or continue to grow by systematic repetition is a relatively small chance. These generalizations can be readily confirmed by pouring out uniform spheres upon a table.

For the time being it may be assumed that the simple rhombic pattern grows to any desired dimensions as the first layer—that the first layer, in fact, contains only this pattern in uniform orientation throughout.

It might be natural to assume that, since the simple rhombic pattern is thus strongly favored for the first layer, it will be at least equally favored for the second and succeeding layers. Such an assumption, however, cannot be granted offhand. Some circumstances tend to increase the probability that whatever type of arrangement is incorporated in the first layer will be repeated in the second and succeeding layers; but other factors tend, on the contrary, to lessen this probability. The resultant of these opposing tendencies cannot always be forecast.

It is evident that the second (and each succeeding) layer cannot accumulate on the smooth horizontal plane postulated as the starting surface for the first layer; instead, it accumulates on the upper surface of the first layer—a surface of alternating hummocks and hoppers. The hummocks and the hoppers are each spaced at systematic intervals determined by the pattern of the layer just completed. If the minimum horizontal intervals between hopper-centers are in all cases exactly $2R$ (as they are in the square layer), then a sphere can settle into *every* hopper and thus form an orderly second layer (this would produce the packing of Case 3). But if the

intervals between hopper-centers are different from $2R$, such an outcome cannot be attained.

As already noted, the top of a layer in simple rhombic arrangement exposes just twice as many hoppers as can be occupied by spheres of the second layer even when this second layer is itself in most compact arrangement, i.e., in simple rhombic arrangement. (It is this 2:1 ratio that permits the twinning of Case 6.) All these hoppers are identical in shape; so any one hopper is as likely to be selected for the repose of a sphere as is any of its neighbors.[27] Yet, if the second-layer spheres do not in every instance faithfully select *alternate* hoppers (leaving the intervening alternates empty [cf. Fig. 7]), the orderliness of the second layer will be broken, and this will happen even though the first layer may be ideally arranged throughout according to the simple rhombic pattern. If the orderliness of the second layer is broken, it will not be repaired in the third layer (or in succeeding layers except by faintest chance.) Instead, the disorder will be perpetuated up into the higher layers and has more than an even chance of becoming further aggravated; for a layer of any given systematic packing ordinarily cannot be larger than the layer of the same packing on which it rests (i.e., without some support from the exterior there can be no overhang), and, if it cannot be larger and there can be no overhang, it follows that each succeeding layer will be smaller than the one below. Therefore, upward propagation from any given area of the simple rhombic layer, unless aided by just the right shape of support from the sides, tends to produce an upward-converging pyramidal "colony" of Case 6 packing; and between such colonies of decreasing size upward, the proportion of haphazard packing increases.

Granted, then, that the simple rhombic arrangement is the one most probable to be adopted in the first layer, the chance that this same arrangement will be continued in higher layers is dependent on whether each sphere settles in the "right" or in the "wrong" hopper. Since the right and wrong hoppers are equal in shape and number, the chance that the right hopper will be chosen would appear to be one out of two—that is, an even chance. But the follow-

[27] See p. 832 for partial qualification of this statement.

30 feet below the ground surface stands in contradiction to statements that exfoliation originates through temperature changes, causing unequal expansion of minerals.[24] It seems probable that exfoliation is to a large extent controlled by the penetration of moisture. In some cases the layering is horizontal, parallel to the ground

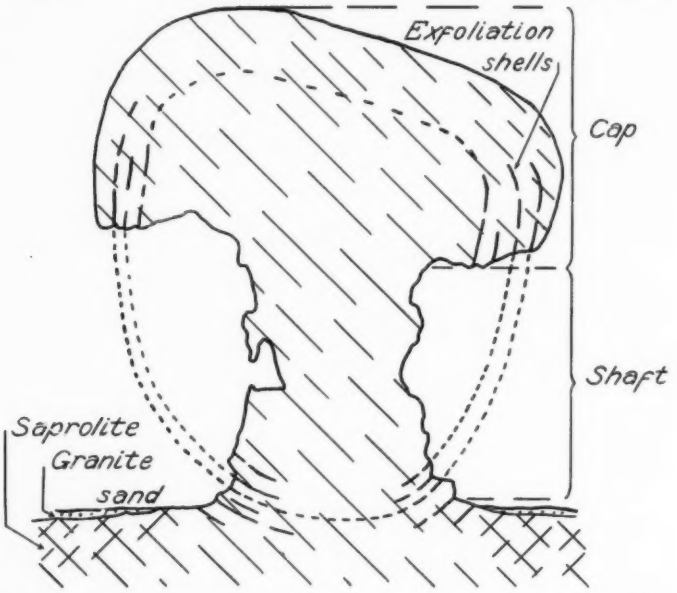


FIG. 8.—Ideal section of a granite pedestal rock, showing relation of exfoliation shells. Compare with Figures 2 and 4.

surface, and so strongly developed that it takes on much the appearance of gneissic banding. The sharp demarcation of cap and pedestal is commonly determined by the truncation of exfoliation shells as shown in Figure 8. The instability of vertical shells that formerly encased the pedestal is apparent.

Petty[25] has noted that the cap of some pedestal rocks in South

[24] Eliot Blackwelder, "Exfoliation as a Phase of Rock Weathering," *Jour. Geol.*, Vol. XXXIII (1925), pp. 793–806.

[25] *Op. cit.*, p. 122.

Carolina is protected by an iron-stained crust. The deposition of this iron oxide, called "case-hardening" by Anderson,[26] has resulted in the development of a weird and remarkable series of forms in the "Cassia City of Rocks," Cassia County, Idaho. In most of the rocks of the southern Piedmont "case-hardening" is a relatively unimportant factor in the preservation of the cap, probably owing to the fact that most of the southern granites contain less than 1.75 per cent iron oxides.

Although it is true that the pedestal rocks are found only on uplands, they most commonly occur near areas of more recent dissection. Many rest on ground slightly below the level of the upland. It is possible that the tops of such rocks represent the level of the adjoining erosion surface. Most of these old surfaces are undulating and close correlations of altitudes cannot be made.

The ultimate origin of the granite blocks from which the pedestal forms developed is not, it seems to me, an important question. They may have been joint blocks or simply knobs on former flat rock exposures. It is apparent that any irregularity that projected above the ground possessed a far better chance to survive disintegration and decomposition to saprolite than adjoining rock that did not have the advantages of drainage.

PHYSIOGRAPHIC SIGNIFICANCE

There is little evidence on the age of the pedestal rocks here described. Their restriction to uplands, interpreted as old erosion surfaces (probably of Tertiary age), has previously been noted. Apparently granite more recently uncovered in valleys has not been exposed long enough to develop either a pitted and grooved surface or the pedestal form. In this connection it is interesting to note that the "weather pits" in granite in Yosemite Valley are thought by Matthes to develop at an extremely slow rate for "not a single one is to be found within the area that was covered by the [last Pleistocene glaciation]."[27] Although climatic conditions in the two regions are somewhat different, the "weather pits" are quite similar to depres-

[26] *Op. cit.*, p. 57.

[27] François E. Matthes, "Geologic History of the Yosemite Valley," *U.S. Geol. Surv. Prof. Paper 160* (1930), p. 64.

sions and grooves on pedestal rocks in the southeast. As a working hypothesis, I suggest that the occurrence of pedestal rocks and related disintegration boulders containing "weather pits" resting on an upland of the Appalachian Piedmont may be regarded as indicating an old erosion surface. Whether the relative ages of erosion surfaces can be determined by the relative development of these residual forms is uncertain.

GEOLOGIC DEDUCTIONS FROM EARTHQUAKES OF DEEP FOCUS

J. S. DE LURY
University of Manitoba

ABSTRACT

From the maze of geophysical data little concrete evidence emerges to permit widely acceptable views on the strength of rocks at different depths in the earth's interior. Seismologists have established the existence of a high degree of rigidity down to great depths, but the commonly held view that earthquakes are of shallow origin has lent support to the opinion that correspondingly shallow rocks alone can permit the slow accumulation of elastic stresses. This opinion must change with the growing evidence that earthquakes probably originate in all levels down to depths of 700 or more kilometers. The same evidence is disturbing to the assumptions of isostasy and to those hypotheses which rest on the concept of a shell of weakness.

Attempts to explain the causes of earth-movements commonly begin with deductions from phenomena and structures which are regarded as effects of the movements. The relative success of competing hypotheses is measured by their ability to explain effects and to meet the limitations which are placed by geophysical evidence regarding the nature of the earth's interior. It might properly be inferred from the diversity of tectonic hypotheses that geophysical data offer few restraints to speculation. Nearly all hypotheses, however, submit to one limitation, that imposed by an acceptance of the principle of isostasy, and with it, the assumption of a continuous shell of weakness beneath a strong crust.

Seismology has exercised a profound influence on speculations regarding the nature of the interior of the earth. The speed of transit of seismic vibrations through all parts of the earth has established the existence of great rigidity in all levels, except possibly in a remote and central core. The earth's reaction to tides and to other outside forces indicates not only a rigidity of the same high order for the earth as a whole, but also great viscosity. Isostasy, however, seems to require that a continuous shell, beneath an admittedly strong crust, must be weak enough to permit a delicate balance in the crust. To reconcile all lines of evidence, it became necessary to assume that rocks in the shell where isostatic adjustments are effect-

ed, notwithstanding their great rigidity, must be nearly devoid of strength when opposed to small stresses of long duration. But the work of Adams and his associates indicates that, other things being equal, rock increases vastly in strength under confining pressures which are known to increase with depth.[1] The only important factor which could be summoned to offset the effect of pressure on strength is heat. Therefore, to permit the existence of a continuous shell with high rigidity and little permanent strength, it had to be assumed that a rather delicate adjustment between temperature and pressure persists throughout the shell of weakness. Not only must conditions be close to those required for fusion, but temperatures must be uniform throughout each level in the shell. Herein probably lies the explanation of the common assumption embodied in many hypotheses, that isotherms are smoothly concentric outward from the earth's interior into surprisingly shallow levels. The writer already has shown that geothermal evidence points very definitely to the conclusions that isothermal surfaces are irregular down to depths of several hundred miles and that thermal conditions decree inequality of strength in any level and a general increase of strength with depth.[2] The purpose of the present paper is to examine in a general way the bearing of the evidence of deep-focus earthquakes on the question of strength in different levels in the earth.

EARTHQUAKES OF DEEP FOCUS

Although the phenomenon of deep-focus earthquakes has long been suspected, it is only in the past few years that methods of estimating depth of origin have been perfected and a sufficient number of reliable records established to permit geologic applications.

As late as 1933, Daly, in listing the evidences in support of the concept of a weak shell, gave what might be regarded as the prevalent view of holders of that conception concerning the levels in which earthquakes originate:

> A fourth evidence is the general, though probably not absolute, restriction of earthquake foci to depths less than 50 kilometers, below which it is doubtful that considerable elastic stress can be accumulated. Much deeper foci of rela-

[1] F. D. Adams and J. A. Bancroft, "Internal Friction in Rocks," *Jour. Geol.*, Vol. XXV (1917), pp. 634–35.

[2] J. S. DeLury, "The Strength of the Earth," *Jour. Geol.*, Vol. XLI (1933), pp. 748–56; "The Magmatic Wedge," *Amer. Jour. Sci.*, Vol. XXVIII (1934), pp. 341–52.

tively weak earthquakes may be expected if the earth has been distorted (as by glacial loading and unloading) at a time so recent that the elastic strain of the deeper shells has not yet had time to disappear. However, seismologists are impressed with the comparative shallowness of most of the determined foci. For example, Jeffreys concludes that the foci of great shocks seem to lie no deeper than 35 kilometers below the surface, and that notable strength is restricted to a shell of the order of 35 kilometers in thickness.[3]

Although these views are of comparatively recent date, neither authority could continue holding them in the light of the evidence of deep-focus earthquakes which has accumulated during the past few years.

No desirable purpose would be served, even if the writer were competent, in attempting to outline and weigh the various methods which have been used to determine the focal depth of earthquakes. Methods are ably discussed by Stechschulte and Scrase, whose papers contain important references to other workers.[4] The direct concern of the geologist is with the statistical data of deep-focus earthquakes, which are already available from the findings of seismologists. Table I is compiled from comparatively limited sources,[5] but it serves all the more from its limitations to indicate that foci occur at great depths and in a wide variety of depths.

GEOLOGIC IMPLICATIONS OF DEEP FOCUS EARTHQUAKES

The evidence that earthquakes may originate at a depth of 700 kilometers and the probability that their foci will be established in all levels down to that depth will place stricter limitations upon hypotheses of earth-movements than do any other geophysical data. It is reasonably certain that at least the deeper earthquakes are caused by an elastic rebound in rocks which slip because their strength has been overcome by slowly accumulated elastic stress. It is probably true that greater stress is needed to cause slipping at

[3] R. A. Daly, *Igneous Rocks and the Depths of the Earth* (1933), pp. 197–98 (with reference).

[4] V. C. Stechschulte, S.J., "The Japanese Earthquake of March 29, 1928, and the Problem of Depth of Focus," *Seis. Soc. Amer. Bull. 22* (1932), pp. 81–137; F. J. Scrase, "The Characteristics of a Deep Focus Earthquake," *Phil. Trans. Roy. Soc.*, ser. A, Vol. CCXXXI (1933), pp. 207–34.

[5] G. J. Brunner, S.J., "The Earthquake of September 6, 1933, and Its Bearing on the Problem of the Deep Earthquake," *Trans. Amer. Geophys. Union* (1934), pp. 72–77; "Earthquake of June 29, 1934," *Prelim. Bull. Central Station, Jesuit Seis. Assoc.* (March, 1935); *Jesuit Seis. Assoc. Bulls.* (1934–35).

great depth than in shallow levels, so that greater strength in rocks is needed to permit earthquakes of deep focus. In the quotation from Daly in the earlier part of this paper, it is clearly implied that if strong earthquakes originate in any level, considerable elastic stress can accumulate in that level, and, therefore, strength comparable to, and probably greater than that of the crust must exist there. Shal-

TABLE I

RANGE OF FOCAL DEPTHS OF EARTHQUAKES IN RECENT YEARS

Approximate Depth in Kilometers	Date	Authority
50	Nov. 5, 1934	Jesuit Seismol. Assoc.
65	July 18, 1934	Jesuit Seismol. Assoc.
75	Feb. 25, 1935	Jesuit Seismol. Assoc.
100	Dec. 23, 1934	Jesuit Seismol. Assoc.
100	Dec. 24, 1934	Jesuit Seismol. Assoc.
100	Feb. 13, 1935	Jesuit Seismol. Assoc.
100	Feb. 20, 1935	Jesuit Seismol. Assoc.
100	Mar. 17, 1935	Jesuit Seismol. Assoc.
200	Dec. 4, 1934	Jesuit Seismol. Assoc.
200	Feb. 28, 1935	Jesuit Seismol. Assoc.
200	Since 1918	Scrase
300	Since 1918	Scrase
360	Feb. 20, 1931	Scrase
410	Mar. 29, 1928	Stechschulte
570	May 26, 1932	Brunner
637	Sept. 6, 1933	Brunner
700	June 29, 1934	Brunner

low earthquakes are the most destructive but there is evidence to show that deep-focus earthquakes may be stronger than the more destructive kind with shallow origin. For example, Scrase wrote of the 1931 earthquake near the Sea of Japan:

> Wadati mentions that the shock of February 20, 1931, was felt in many parts of Japan and as far away as 1,300 kilometers from the epicenter. On the other hand, the disastrous Tokyo earthquake of September, 1923, which was very much more violent, was not perceived at all at distances greater than 800 kilometers. This difference is, of course, in accordance with the idea that the shock of February, 1931, was of considerably deeper focus than the Tokyo earthquake.[6]

Seismologists were early in grasping the geologic significance of deep-focus earthquakes. After indicating the evidence of deep foci, Macelwane stated:

[6] *Op. cit.*, p. 210 (with reference).

What would be the mechanism of displacement at these greater depths remains an open question since fractures seem very improbable.[7]

Stechschulte went further:

The occurrence of earthquake-shocks at depths of three, or four or even five hundred kilometers may, I think, be taken as well established, though the processes by which such shocks originate is [*sic*] not at all clear. It would also seem that the occurrence of such deep-seated shocks must be taken into account in our study of the character of the Earth's interior, as perhaps also in such problems as the depth of isostatic compensation and the like.[8]

The most obvious conclusion from deep-focus earthquakes is that strength in general increases with depth. It is inconceivable, therefore, that a continuous shell of weakness can exist, if the remote central core is excluded from consideration. What explanation can be offered of the mechanism of deep seismic disturbances? Tides and other external forces produce only minor distortional effects and apparently they have no accumulative effect. Changes of load at the surface, brought about by gradation processes and by the accumulation and melting of ice sheets, might conceivably lead to deep disturbances, but are more likely to produce deformations within the elastic limit. It is not easy to imagine violent repercussions at depths of 700 kilometers from the melting of an ice sheet. Deep-seated earthquakes call for mighty stresses, and in the dilemma, it seems necessary to appeal to the greatest source of energy in the earth, namely, heat.

If geo-isotherms were smoothly concentric outward to a depth of 100 kilometers from the surface, the deepest earthquakes could only be explained by the collapse of an outer shell, 700 or so kilometers thick, to accommodate itself to a core which is suffering thermal contraction. Such collapses would likely be sudden, catastrophic, and infrequent. But deep-focus earthquakes are neither infrequent nor catastrophic. The wide range in radial distribution of deep disturbances, and their apparent localization in horizontal distribution, suggest differential thermal expansion and contraction, as between wide columns of an outer shell extending down 700 kilometers or more.

[7] J. B. Macelwane, S.J., "Our Present Knowledge Concerning the Interior of the Earth," *Seis. Soc. Amer. Bull. 21* (1931), p. 244.

[8] V. C. Stechschulte, S.J., *Trans. Amer. Geophys. Union 14th Ann. Meeting* (1933), pp. 311–12.

The greatest focal depth of an earthquake, so far recorded, is 700 kilometers. Jeffreys[9] estimated that cooling has disturbed the "initial thermal gradient" down to about the same depth. Such a similarity in depth is expected, if deep earthquakes are caused by stresses from differential thermal activities and we assume that the earth has solidified from a former molten state. It is highly probable that earthquakes with deeper foci than 700 kilometers will be found, and that the initial thermal gradient has been disturbed to greater depths. It is possible that in the future a statistical study of deep-seated earthquakes will throw more light upon this problem.

A rational hypothesis for the mechanism of earthquakes of deep origin seems to be permitted by the evidence: If an initial thermal gradient has been disturbed to depths greater than 700 kilometers, rocks above those depths should in general have temperatures sufficiently remote from fusion conditions for the confining pressure to give them great strength. It might be asked, however, if this general condition excludes the possibility of a continuous shell of weakness in shallower levels. In answer it can be said that geothermal evidence is opposed to the existence of a shell of weakness and favors the view that the outer earth is being continually distorted by thermal activities.[10] The evidence that earthquake foci are found at many levels down to depths of 700 kilometers, gives definite confirmation of this view. Expansion and contraction, brought about by differential generation and conduction of heat, in rocks of great strength, seem to be the most promising source for the great stresses required by deep-seated earthquakes.

The conclusions of this paper are directly opposed to hypotheses which are built on the assumption of a continuous shell of weakness, and are equally opposed to the assumptions of isostasy. There is abundant evidence in favor of the general conception of isostasy, but overwhelming evidence against the assumptions upon which the conception has grown. In this dilemma, a re-reading of T. C. Chamberlin's views will be well worth while.[11]

[9] H. Jeffreys, *The Earth* (1929), p. 154.

[10] J. S. DeLury, *op. cit.*

[11] T. C. Chamberlin, "Intrageology-Elastasy *vs.* Isostasy" (Editorial) *Jour. Geol.*, Vol. XXXV (1927), pp. 89–94.

GROWTH STAGES OF *ALLAGECRINUS AMERICANUS* ROWLEY

RAYMOND E. PECK
University of Missouri

ABSTRACT

A study of about three hundred well-preserved calyces of *Allagecrinus americanus* Rowley has shown an unusually complete series of growth stages. The arm facets develop first on the *LAR* and *RPR*, then on the *LPR* and *RAR*, and finally on the *AR*. The anal series is introduced about the same time as the facet on the *AR*. The orderly appearance of arm facets is accompanied by an increase in the size of the calyx, a lessening in the strength of the ornamentation, and a greater differentiation of the radial plates.

Immature crinoid calyces are rare as fossils, and it is very unusual to find a fairly complete series of growth stages. Exceptions to this are found among the Paleozoic microcrinoids, especially among the Allagecrinidae. These minute forms are collected most successfully from very thin shale partings in limestone, and at some localities hundreds of individuals may be taken from comparatively small samples of shale. As the shale samples ordinarily represent an area of but a few square inches it is to be expected that even a large number of individuals may represent only one species. This gives an excellent opportunity for the study of ontogenetic stages.

Wright,[1] working with Scottish representatives of the Allagecrinidae, has established several recognizable stages in the development of *Allagecrinus austinii* Carpenter and Etheridge and other related species. He concludes that, for the most part, the development of arms follows no orderly succession.

Weller[2] has recently studied and redefined *Allagecrinus americanus* Rowley, the only recorded American species of the genus. In his description he implied that some of the smaller individuals in which no anal plate could be detected might represent immature forms.

In order to obtain material for comparison with microcrinoids of

[1] J. Wright, "Scottish Species of *Allagecrinus*," *Geol. Mag.*, Vol. LXIX (1932), pp. 337–66. See also J. Wright, "Two New Crinoids from the Scottish Carboniferous Limestones, with Notes on the *Allagecrinidae*," *ibid.*, Vol. LXX (1933), pp. 201–8.

[2] J. Marvin Weller, "A Group of Larviform Crinoids from Lower Pennsylvanian Strata of the Eastern Interior Basin," *Ill. Geol. Surv. Rept. Investigations 21* (1930).

the Fern Glen and Chouteau (Kinderhookian) formations I visited the type locality of *Allagecrinus americanus* Rowley. The late Professor R. R. Rowley was kind enough to accompany me and point out the exact locality and horizon from which he obtained the type material. Two small samples collected there yielded over 300 well-preserved crinoid calyces. These calyces vary greatly in size, in relative proportions of the plates, and in the number of arm facets. At first I was inclined to recognize at least two distinct species and possibly two genera; but further comparison and study showed that they illustrated a remarkable series of growth-stages.

Allagecrinus americanus ROWLEY

1895. *Allagecrinus americanus* Rowley, *Amer. Geol.*, Vol. XVI, p. 219, Figs. 3–10.

1908. *Allagecrinus americanus* Rowley, *Mo. Bur. Geol.*, Ser. II, Vol. VIII, p. 67, Pl. 16, Figs. 39–41.

1930. *Hybochilocrinus americanus*, J. Weller, *Ill. Geol. Surv., Rept. Investigations 21*, pp. 12–15, Pl. 1, Figs. 1*a*, 1*b*, 1*c*.

1933. *Allagecrinus americanus*, J. Wright, *Geol. Mag.*, Vol. LXX, p. 205.

Calyx pyriform to elongate pyriform, small, seldom attaining a height of over 1.3 mm., consisting of a low basal circlet in which the sutures are unknown, five elongate radials that make up more than one-half the body height, five orals of nearly equal size, the posterior oral being slightly larger than the other four and, in the adult, an anal series originating on the excavated left shoulder of the *RPR* (Fig. 1, *1–11*). The radials are of almost equal width on young forms but are differentiated with later growth so that the *LAR* is always distinctive by being narrow with almost parallel sides, and the two posterior radials become wider than any of the other three. Immature forms are armless, the outer edges of the orals meeting flush with the outside edges of the radials, the arms being introduced on the *RPR* and *LAR* first, then on the *LPR* and *RAR*, and finally on the *AR*. On the majority of representatives there is one arm to a radial but the radials may be axillary. Oral dome prominent in the young, making up almost one-third of the entire height of calyx, becoming less prominent with growth until on the mature form it makes up about one-sixth of the total height. Orals concave with raised borders, the concavity of the posterior oral being interrupted

near the center of the plate by a short ridge or tubercle that probably represents the hydropore. Anal series introduced about the same time as the formation of the arm facet on the *AR* and originating in an excavation on the left shoulder of the *RPR*. First plate of the anal series long and slender with parallel sides, other anals not preserved. First primibrachs simple, slightly longer than wide, others

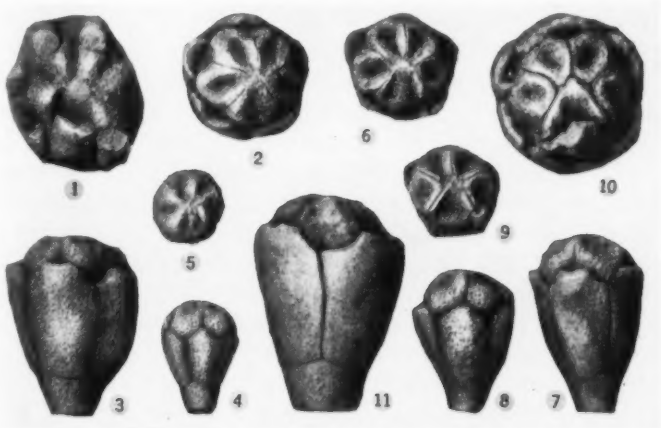


FIG. 1, ILLUSTRATIONS *1–11*.—*Allagecrinus americanus* Rowley. All specimens enlarged twenty-eight diameters. 1. A large individual with brachials in place on *AR*, *LAR*, *RPR*, and anal plate on left shoulder of *RPR*. *2* and *3*. Lateral (*LPR*) and summit views of specimen with five arm facets and slight differentiation of left shoulder of *RPR*. *4* and *5*. Lateral (*RPR*) and summit views of immature armless specimen. *6* and *7*. Lateral (*LPR*) and summit views of specimen with facets on *LAR*, *LPR*, *RPR*, *RAR*, and small facet on *AR*. *8* and *9*. Lateral (*LPR*) and summit views of specimen with facet on *LAR* and first brachial in position on *RPR*. *10* and *11*. Lateral (posterior inter-radius) and summit views of specimen with five arm facets and partially exfoliated anal plate.

not preserved. Ornamentation consists of reticulate meshwork of fairly coarse ridges. The ridges are coarse on the young and become less conspicuous with growth of calyx. Many of the largest forms are almost smooth.

Occurrence.—Shale partings in the lower 3 feet of the Louisiana limestone at the mouth of Buffalo Creek, about one mile south of Louisiana, Missouri.

Figured Specimens.—Catalogue number E-3–5, University of Missouri.

GROWTH-STAGES

The most immature stage of *Allagecrinus americanus* Rowley studied is represented by nine very small specimens, the best preserved of which is illustrated in Figure 1, *4* and *5*. They vary from 0.5 to 0.6 mm. in height and are ornamented by a reticulate meshwork of fairly coarse ridges. This ornamentation is of the same strength on all specimens of this size and on all parts of each specimen so that there is no chance that it was caused by irregular solution or wear. The radials are relatively shorter than in the mature individuals and the oral dome is much more prominent. The radials are all of approximately the same width, but even at this early stage the narrow *LAR* can be readily identified. The posterior radials are of almost exactly the same size as the *RAR* and *AR*. The oral dome is swollen and quite prominent, making up approximately one-third of the height of the entire calyx. The outer edges of the orals are flush with the outer edges of the radials, leaving no possible place for the attachment of arms. There is no anal plate and no evidence that one developed at a later stage. The *RPR* is not differentiated in any way. There is no visible opening into the calyx, although the small knob in the center of the posterior oral (Fig. 1, *5*) is probably the hydropore.

The next recognizable stage shows an increase in height to approximately 0.7 mm. Some thirty specimens of this stage differ from the earlier stage not only in being slightly larger, but in having a slightly less prominent oral dome and by the retreat of the orals from the outer edges of the *RPR* and the *LAR* with the introduction of arm facets. Figure 1, *8* and *9*, show lateral and summit views of a specimen with the first primibrach in position on the *RPR*. The *LAR* and *RPR* are always the first to develop facets, and these two facets are well developed on many specimens in which the outer edges of the other three radials fit closely into the outer edges of the orals. There is no differentiation of the *RPR* at this stage and no evidence of an anal series.

The third stage in the development of *A. americanus* Rowley (Fig. 1, *6* and *7*) is characterized by the introduction of arm facets on

the *RAR* and the *LPR*. Ordinarily these two facets seem to have developed simultaneously, but in rare cases either one developed before the other. The appearance of these two facets is accompanied by an increase in the size of the calyx, a lessening of the prominence of the oral dome and a marked increase in the relative size of the posterior radials. There is, as yet, no definite sign of the anal series of plates or the differentiation of the *RPR* for their reception. All radials, except the anterior, bear arm facets. The ornamentation is still conspicuous.

The last stage (Fig. 1, *10* and *11*), represented by apparently mature individuals, is characterized by the development of an arm facet on the *AR* and the differentiation of the *RPR* by the left shoulder sloping abruptly below the general surface of the radials for the reception of the first plate of the anal series. The anal series and the arm facet on the *AR* may originate simultaneously or either one may develop before the other. This seems to vary greatly on different individuals. In the young forms the oral dome accounted for almost one-third of the entire height of the calyx, but in the mature specimens it makes up only about one-sixth of the total height. There is also a lessening in the strength of the ornamentation and some of the larger forms are almost smooth.

In the original description of *A. americanus*, Rowley[3] notes that the larger specimens among his types possess "scars for the attachment of nine arms." Weller[4] failed to note this stage in his examination of over a hundred individuals of this species, and none of the specimens examined in the preparation of this paper shows more than five arm facets. However, the types have not been re-examined, and considering the tendency for other species of this genus to develop axillary radials, it is quite probable that this stage exists in *A. americanus* Rowley.

In summary, the earliest represented stage of *A. americanus* Rowley consists of a small calyx about 0.5 mm. high with a prominent oral dome, no arm facets, and no anal series. Arm facets are

[3] R. R. Rowley, "Description of a New Genus and Five New Species of Fossils from the Devonian and Sub-Carboniferous Rocks of Missouri," *Amer. Geol.*, Vol. XVI (1895), p. 219.

[4] *Op. cit.*, p. 14.

developed first on the *RPR* and *LAR*, then on the *LPR* and the *RAR*, and finally on the *AR*. Accompanying the introduction of the facet on the *AR* is the development of an anal series on the left shoulder of the *RPR*. These changes are accompanied by an increase in the size of the calyx, a decrease in the strength of the ornamentation, a lessening of the prominence of the oral dome, and a greater differentiation in the width of the radials, the two posterior radials becoming much wider than the other three.

HOW MANY GLACIAL STAGES ARE RECORDED IN NEW ENGLAND?

RICHARD FOSTER FLINT
Yale University

It is said that during the time when the fourfold glacial succession was being established in the Mississippi Valley region, geologists working on the Pleistocene of the Mississippi Valley looked down upon the geologists working on the Pleistocene of New England because of their apparent inability to read in the New England drift an equally long and complex history. It is to the New Englanders' credit that most of them did not read a complex history *into* their drift. The great relief, hilly character, and dominantly resistant rocks of New England, coupled with its lack of a driftless area, and last but by no means least its coastal position (so that much of its drift-border zone has been submerged in the rising postglacial sea), make the recognition and evaluation of pre–Late-Glacial features a more difficult matter than in the low-relief, weak-rock region in the heart of the continent.

The coastal plain, unfortunately now mostly submerged, is the most promising hunting ground in New England for pre–Late-Glacial Pleistocene geology, for two reasons: first, it lies in the drift-border zone, where glacial erosion must have been relatively weak and of short duration, and therefore less likely to destroy earlier deposits; second, it is a region of slight relief, thereby favoring the development of unit features, such as recognizable strata, ice-thrust phenomena, and end moraines, more or less continuously along considerable stretches of ice front. The value of this hunting ground has been recognized in that the glaciated coastal-plain region has been a field of intensive investigation since Shaler's time. The two most modern single studies are represented by the work of M. L. Fuller on Long Island[1] and the contemporaneous but more recently

[1] M. L. Fuller, "The Geology of Long Island, New York," *U.S. Geol. Surv., Prof. Paper 82* (1914).

published study of the Cape Cod district[2] by Woodworth and Wigglesworth. The stratigraphic conclusions reached in the latter work parallel those reached in the former, in that they involve the recognition of four distinct glacial stages separated by interglacials. The writer believes that the local mapping and the local interpretations involved in this work are of a high order, but is not convinced that all the wider interpretations and correlations are justified by the facts. Therefore, in spite of the respect which the nature of the study inspires, certain points involving doubts and disagreements are here discussed, chiefly because the writer claims some familiarity with the geology of Cape Cod and Long Island, and holds somewhat different views, the comparative value of which further study and discussion will determine.

Pleistocene glacial stratigraphy is ordinarily much more complex than, for instance, Paleozoic marine stratigraphy. Changes in lithology and in mode of deposition are apt to be abrupt both laterally and vertically, so that conditions between exposures cannot be inferred with confidence. There are few fossils to aid correlation. The non-consolidated nature of the deposits favors slumping, which quickly covers the faces of exposures, making restudy difficult if not impossible. For these reasons, long-distance correlations of small units are hazardous even after very detailed field study. For example, a general agreement between the Pleistocene glacial stratigraphy of Long Island and that of Cape Cod is expectable, but detailed agreements and continuity of many individual beds along an ice front of 200 miles seem much less likely.

The composite column for Cape Cod as interpreted by Woodworth and Wigglesworth is given in Table I. The points of correspondence with Fuller's Long Island column[3] are immediately apparent.

If these correlations are valid, then we have in the Cape Cod region a remarkably complete representation of the Pleistocene column, as we understand it from the Mississippi Valley region. In the type localities in that region, the basis of separation of the several

[2] J. B. Woodworth and Edward Wigglesworth, "Geography and Geology of the Region Including Cape Cod, the Elizabeth Islands, Nantucket, Marthas Vineyard, No Mans Land and Block Island," *Mem. Harvard Mus. Comp. Zoöl.*, Vol. LIV (1934).

[3] *Op. cit.*, table facing p. 220.

drift sheets consists ideally of (1) tills or other drift deposits of types that are distinctive because they derive from different ice centers, (2) separated by zones of marked weathering and/or distinct interglacial deposits. All the Cape Cod ice evidently came from the Labrador center; hence the Cape Cod drifts cannot be separated on

TABLE I

Cape Cod District	Correlation
Wisconsin deposits (Nantucket and Falmouth moraines and Plymouth interlobate moraine)	Wisconsin
Vineyard erosion interval	Peorian Iowan Sangamon
Manhasset formation { Hempstead gravel Montauk till	Illinoian
Jacob sand (transitional from Gardiners clay)	
Gardiners clay (marine)	Yarmouth
Jameco formation { Moshup till Coarse gravel Boulder bed	Kansan
Mannetto clay-till and gravel Weyquosque glacial sand, and Sankaty (marine) sand Dukes boulder bed	Nebraskan
Aquinnah conglomerate (non-glacial, probably fluvial)	

a regional-lithologic basis. Beyond this, the stratigraphic evidence offered in support of the correlation given above is meager. Let us consider the non-glacial members of the sequence. The Aquinnah conglomerate is preglacial and is therefore of no value in the present discussion. The Sankaty sand, exposed on Nantucket, carries marine invertebrate fossils, but it is locally much contorted and its position in the column is uncertain. Wilson[4] regarded it as transitional upward into the Wisconsin glacial deposits. Fuller[5] placed it in the

[4] J. H. Wilson, *The Glacial History of Nantucket and Cape Cod* (New York, 1906), pp. 29–30.

[5] *Op. cit.*, p. 92.

Manhasset formation, below the Montauk till. Woodworth[6] was inclined to place it much lower in the column, on the ground that the overlying till resembles the Moshup till of Marthas Vineyard. Until the position of the Sankaty beds is agreed upon, we are left with only one horizon of manifestly non-glacial character and undoubted stratigraphic position in the entire column: the Gardiners clay. Not even this bed is surely interglacial. For though in one place[7] Woodworth and Wigglesworth state that this clay "was doubtless laid down during an interglacial stage," they say elsewhere[8] "whether the clay is of interglacial or glacial origin cannot be determined, but it is not necessarily interglacial, for all the conditions requisite to its deposition would have existed when the ice front stood some distance back of this area. . . . . Thus the Gardiners clay is considered a glacial or an interglacial marine deposit. . . . ."

One can scarcely avoid the conclusion, in view of these facts, that the correlation of distinct glacial stages in the Cape Cod region rests on uncertain ground.

The next question concerns the separate identity of the Dukes-Weyquosque-Mannetto sequence and the threefold Jameco sequence, both shown in Table I. Each sequence consists of boulders, gravel, and stony blue clay. The two sequences do not occur in the same section, nor do all three members of one sequence occur in any one section. The two standard sections, both strongly folded and overthrust, occur in the Gay Head cliffs on Marthas Vineyard, and in the Nashaquitsa Cliffs, 5 miles southeast on the same island. The Gay Head section exhibits the Dukes boulder bed, the Mannetto till, and an overlying gravel of doubtful correlation. The Nashaquitsa section exhibits the Weyquosque gravel and the Moshup till. The only other section in which a pre-Gardiners till is mentioned is on No Mans Land, 7 miles south of Gay Head, where a cliff exposes, beneath the Gardiners clay, a till bed referred to the Moshup, although no evidence for this correlation is cited. Thus it appears that all the exposures occur in the same district, that no single section includes more than one pre-Gardiners till, and that the inferred two

[6] Woodworth and Wigglesworth, *op. cit.*, p. 97.

[7] *Ibid.*, p. 50. [8] *Ibid.*, p. 168.

triple sequences exhibit lithologic similarities. Apparently Wigglesworth recognized this, for in describing the Nashaquitsa section he says,[9] "These beds [the Weyquosque and Moshup] therefore resemble the Pleistocene beds in Gay Head, where a bed of stony blue clay simulates [sic] a deposit of till, but the stony blue clay in the Gay Head section is regarded by Professor Woodworth as an older deposit, of Mannetto age."

In the absence of paleontologic evidence, the reason for regarding these two sequences as distinct is not clear to the writer, who submits that on the evidence cited, it is at least equally likely that they should be correlated, as representing a single pre-Gardiners till.

Another question concerns the Vineyard erosion interval, an important element in the column because it is regarded by the authors as the equivalent of at least the Sangamon interglacial of the Mississippi Valley region. Recognition of this interglacial stage of post-Manhasset, pre-Wisconsin date is based on no stratigraphic exposure. According to Woodworth and Wigglesworth[10] the evidence consists of (1) partial adjustment of streams to the ice-deformed surface of pre-Wisconsin beds on Marthas Vineyard, and (2) similarity of certain large valleys between terraces of stratified drift on Marthas Vineyard and Cape Cod, to the valleys forming the harbors between the northern necks of Long Island, regarded by Fuller[11] as records of extensive pre-Wisconsin fluvial excavation. As evidence for an interglacial stage, the points cited seem inadequate for these reasons: (1) Streams may be expected to assume courses consequent on an undulating surface deformed by ice thrust, immediately upon the uncovering of the surface by the ice. (2) The harbors between the northern necks of Long Island have been held by Crosby[12] and Fleming[13] to be of constructional origin, therefore recording little or no erosion, and of Wisconsin date, and the writer, who has examined

[9] *Ibid.*, p. 166.

[10] *Ibid.*, pp. 56, 189, 261–64.

[11] *Op. cit.*, pp. 45, 208.

[12] W. O. Crosby, "Outline of the Geology of Long Island, N.Y.," *Ann. N.Y. Acad. Sci.*, Vol. XVIII (1928), pp. 425–29.

[13] W. L. S. Fleming, "Glacial Geology of Central Long Island," *Amer. Jour. Sci.*, Vol. XXX (1935), pp. 216–38.

them independently, is in agreement with this opinion. The valleys in the Cape Cod region, cited by Woodworth and Wigglesworth, are believed to be of similar character. (3) No weathering at the surface of the Manhasset formation is reported. (4) Sea level should have been relatively high during an interglacial stage, thus providing conditions for marine deposits somewhat like the Gardiners clay, rather than conditions for the deep erosion described. (5) Fleming[14] has pointed to several lines of evidence against the existence of an erosion interval at this time on Long Island.

The problem of the Vineyard interval is closely bound up with the correlation of the Manhasset and Wisconsin deposits. If the Vineyard interval be deprived of the interglacial standing attributed to it by Woodworth and Wigglesworth, it is difficult to understand why the Manhasset formation should be regarded as distinct from the Wisconsin. On this head no evidence, other than the questionable points relating to the Vineyard stage, is adduced. Yet facts mentioned in their memoir point to the desirability of grouping the two within a single glacial stage:

> The boulders in the Montauk [Manhasset] till, which were imbedded in impervious clay, are fairly fresh looking. Many of them are less weathered than the Wisconsin boulders. . . . .[15]
>
> The lithological similarity of the Pleistocene beds is particularly marked in the waterlaid deposits of the Manhasset formation and in the Wisconsin deposits. . . . . The upper and lower members of the Manhasset formation could not be told apart were it not for the bed of till (Montauk till member) that separates them, nor could these two beds of Manhasset gravel be distinguished from the outwash gravel of the Wisconsin stage except by considering the difference in their distribution. The Wisconsin till, although it is usually much sandier than the till member of the Manhasset, is at some places so nearly like the Manhasset till that it can be distinguished only by its position and by the fact that it is separated from the Montauk till by a bed of gravel.[16]

That the Manhasset and Wisconsin deposits in Long Island are referable to a single glacial stage has been specifically held by Crosby,[17] Fleming,[18] and Wells.[19] The writer's own field study has

[14] *Ibid.* [15] Woodworth and Wigglesworth, *op. cit.*, p. 55.

[16] *Ibid.*, p. 137. [17] *Op. cit.* [18] *Op. cit.*

[19] F. G. Wells, "Reconsideration of the Pleistocene Geology of Long Island," Geol. Soc. Amer., December meeting, 1934 (abst.).

led him also to this view. As the Manhasset and Wisconsin deposits in the Cape Cod region are in general much like those of Long Island, definite evidence of separate identity must be made available before they can be widely regarded as distinct.

If these criticisms are valid, at most only two glacial stages, instead of four, are represented in the Cape Cod Pleistocene column. Even the Gardiners clay, the most distinctive member of the sequence, on the showing of Woodworth and Wigglesworth, is not certainly of interglacial character, although MacClintock and Richards[20] have recently suggested its correlation with the Cape May formation of New Jersey, a deposit having a marine phase with a warm-habitat fauna. But in spite of the doubt, the Gardiners clay is definitely marine and reasonably distinctive, and therefore serves as a kind of key bed or reference bed. Below it we have at least one till; above it we have at least the Wisconsin sequence. There are intervening unconformities, to be sure, but in the narrow ice-margin zone of the Cape Cod region, repeated short-term oscillations of the ice front must be regarded as likely, and the unconformities are of a type attributable to this mechanism.

This fact should not be lost sight of: The pre-Wisconsin history of the Cape Cod region has necessarily been interpreted thus far on a basis of the very few sections exposed, most of them greatly deformed. As fresh sections appear in wave-cut cliffs we can add to our information. The small body of data now at hand seems to call for the adoption of a conservative attitude—for description in local terms divorced from long-range correlation, which, until supported by stronger evidence than is yet available, will hinder with one hand, while it aids with the other, the clear understanding of the Pleistocene history of northeastern North America.

[20] P. MacClintock and H. G. Richards, "Correlation of Marine and Glacial Pleistocene Deposits of the Middle Atlantic Seaboard," Geol. Soc. Amer., December meeting, 1934 (abst.).

DAVID WHITE

Dr. David White, for many years a valued associate editor of the *Journal of Geology*, died at his home in Washington, D.C., February 7, 1935, at the age of seventy-two.

White obtained his elementary education in country schools near his birthplace in Palmyra Township, Wayne County, New York, and prepared for college at Marion Collegiate Institute, where, under an inspiring teacher, he developed an enthusiastic interest in the systematic botany of the region. His academic training in geology and paleontology was received under Samuel Gardner Williams, Charles L. Prosser, and Henry S. Williams, at Cornell University, where he won early recognition as an exceptional student in such diverse subjects as geology, drawing, and veterinary science.

White's training in botany, geology, and drawing prepared him for service in the United States Geological Survey, where his first assignment, in 1886, immediately after graduation from Cornell, was to make accurate pencil drawings of fossil plants for Lester F. Ward, then in charge of the paleobotanic work of the Survey. Ward had developed a method of using drawings of selected specimens, rather than the fossils themselves, in making systematic comparisons for purposes of identification and description. White was soon placed in charge of this illustrating and a little later was given direction of the extensive bibliographic work in paleobotany that Ward was then inaugurating.

In the early nineties Ward and Fontaine were actively investigating the earlier Mesozoic floras, and Knowlton was describing the floras of the Tertiary and the Upper Cretaceous; but the very important field of Paleozoic paleobotany was practically unoccupied, as far as the Geological Survey was concerned, until White made it his own. Beginning in the Appalachian coal fields where the Geological Survey was then actively engaged in areal mapping, White took up the field and laboratory study of the floras and their stratigraphic relations with the enthusiastic energy and thoroughness that was characteristic of everything he did. Working in close co-

operation with the geologists who were mapping the coal fields, he was soon able to convince them that from his knowledge of the associated floras and their distribution he could not only classify and correlate the formations from field to field over large areas but could also often identify individual coal beds throughout a field, and thus solve problems of stratigraphy, structure, and correlation where other lines of evidence were obscure or misleading. His field studies in paleobotany were extended to New England, the Mississippi Valley, the Southwest, and in later years to the Rocky Mountains and the Grand Canyon region. They embraced the entire Paleozoic and extended into the pre-Cambrian, though his major interest in paleobotany was the Pottsville (early Pennsylvanian) flora, which he studied as opportunity offered throughout his professional career. A large part of this flora as developed in Illinois and neighboring states was described in a manuscript monograph which was nearing completion when his last day's work ended.

White's pre-eminence as a paleobotanist and stratigrapher is unquestioned, but his original contributions to general geology and his personal influence on the development of the science extended into much broader fields. He could not escape the burden of administrative work that so often comes to scientific men who are attached to government bureaus and educational institutions, but to him the added responsibilities and routine duties were only a stimulus to undertake and direct other lines of research. In the Geological Survey he supervised the geologic work in eastern coal fields, then had general direction of surveys in oil and gas fields, and served for ten years, including the World War period, as chief geologist. His much-desired return to paleobotanic research was again delayed by three busy years of service as chairman of the Division of Geology and Geography in the National Research Council and by special duties in the National Academy of Sciences, first as home secretary and afterward as vice-president. Even in the midst of these varied duties, he was making important contributions to isostasy and to the development of methods by which the essential data needed for its problems may be collected; he was demonstrating the important aid that geology may give a nation in the economic crisis caused by war; and he was doing pioneer work on the origin and evolution of coal

and petroleum. In connection with the latter studies he made a very important generalization about the relation between possible oil production and the fixed carbon ratio of associated coals, to the effect that commercial production of oil should not be expected from rocks associated with or underlying coals in which the regional alteration had brought the fixed carbon up to 65 or 70 per cent of the coal, reckoned as pure coal without ash. This carbon-ratio theory, which should prevent enormous waste of capital in many areas where exploration for oil would be profitless, was first announced in the *Journal of the Washington Academy of Sciences*, Vol. V (1915), p. 212, and was more fully elaborated and revised in a posthumous paper in the *Bulletin of the American Association of Petroleum Geologists* (May, 1935).

The many honors that came to Dr. White in recognition of his scientific work have been enumerated elsewhere. They were all deserved. Adored by members of his own household, loved by those privileged to be his close associates, honored by all who knew him, David White met the essential requirements of religion, in that throughout his life he obeyed the injunction to do justly, to love mercy, and to walk humbly with his God.

T. W. STANTON

REVIEWS

Geology of Vitilevu, Fiji. By HARRY S. LADD. Bernice P. Bishop Museum Bull. 119. Honolulu: Museum, 1934. Pp. 263; figs. 11; pls. 44; tables 7.

Fiji affords an interesting field both to the general geologist and particularly to the student of Pacific paleontology because of a rather general belief that it is of continental origin. Lithologically the islands of the Fiji archipelago combine various rock types commonly associated with continental masses, together with others which characterize the volcanic islands of the mid-Pacific.

The rocks of Vitilevu comprise a pre-Tertiary series of plutonics and more or less metamorphosed volcanics and sediments, which form the core of the island, and a younger series of relatively unaltered rocks of Tertiary age. The plutonics include granite, quartz-monzonite, quartz-diorite, diorite, and gabbro, though these types are much more closely related petrographically than their names indicate. Most of them are fine-medium to medium grained. Some of the metamorphic rocks which they intrude exhibit a slaty structure, but schists and gneisses are absent.

The younger series is composed predominantly of pyroclastic material, much of it reworked. The Viti formation in the middle of the series is primarily a massive foraminiferal limestone reaching 200–300 feet in thickness. Corals are almost entirely wanting, suggesting that this limestone of early Miocene age was deposited on a sea floor below the depth of reef-coral growth. Volcanic activity continued into the Pleistocene but died out before its close.

The author distinguishes between "oceanic islands, composed entirely of volcanic rocks and organic limestone, or sediments derived from these," and "continental islands made up of plutonic or metamorphic rocks in addition to the types of rock found on oceanic islands. . . . . As shown on the map (Fig. 6), all of the continental islands lie west of an imaginary line drawn from Yap southeastward through Truk, New Ireland, the Solomon Islands, and Fiji to Tonga, thence southwestward through the Kermadecs to include New Zealand and certain of its outlying islands." Because of this observation the author extends the Philippines, East Indies, and Australia out to this line to comprise "the former Melanesian continent." This continent is treated as if its verity were established.

Its heart is Australia; within an arc swinging from Borneo through New Guinea, New Zealand, and Tasmania, Paleozoic rocks are found; and within the arcuate imaginary outer line, postulated as the boundary of the continent, Mesozoic rocks occur.

"The destruction of the Melanesian continent was one of the major events of earth history." But how did it take place? Normal faulting due to tension is suggested by the author. One may well wonder, however, how to picture the dropping of such vast areas thousands of feet by normal faulting and what became of the underlying rock material. The areas now submerged to abysmal depths are of much greater extent than the island ridges. What made the ridges now relatively so high standing? Dynamically and mechanically this concept seems to the reviewer a difficult one to accept.

Is it not simpler to regard the individual island ridges as upfolded strips of ocean floor arising from the depths? Not a few of them seem to be comparable in magnitude to the Sierra Nevada Mountains of California where schists and gneisses (absent in Vitilevu) were strongly developed and great masses of granodiorite were injected as batholiths. Can it be affirmed confidently that the chemical composition of the Vitilevu plutonics is such that they could not have come from beneath the Pacific? Australia was a continental mass as early as pre-Cambrian times, exhibiting rocks contorted in pre-Paleozoic orogenies. The inner zone of surrounding islands (Borneo, New Guinea, New Zealand, and Tasmania) contains Paleozoic rocks. Early upfoldings of the necessary strips of the ocean floor at appropriate times would explain this fact. The islands of the outer belt contain Mesozoic rocks. Later upfoldings would explain this. Perhaps we see a continent in the process of development, growing and enlarging outward from the Australian shield by successive increments of folding, rather than an old continent undergoing dismemberment. This alternative is not considered in the discussion. Under either hypothesis, extensive faulting is to be expected in strips of islands undergoing deformation, and the extravasation of lavas and outbursts of pyroclastics are the natural accompaniment.

The bulletin also contains sections on the petrography, by Arthur A. Pegan; smaller foraminifera, by Joseph A. Cushman; larger foraminifera, by G. Leslie Whipple; corals, by J. Edward Hoffmeister; smaller echinoids, by H. L. Hawkins; and decapod crustaceans, by Mary J. Rathbun.

It is interesting to note that the Fijian faunas are more closely related to the Tertiary faunas of the tropical East Indies than to those from sections in New Zealand and Australia which lie somewhat closer but in more

southerly latitudes. "Eventually, with the aid of intermediate localities such as those in India, it may be possible to correlate the late Tertiary sections of the southwest Pacific with those of Europe in a satisfactory manner, but at the present time it is impossible to say with any assurance that what is called Miocene in the East Indies is the exact equivalent of what is defined as Miocene in the type sections of Europe." The term "Miocene" is accordingly used in this report for what has been called Miocene in the East Indies. Many species of invertebrates have been described and figured in plates and not a few new species added.

The bulletin is a comprehensive, well-rounded piece of work of much interest and unusual value because of the important contributions which it makes to many different geologic problems. The natural difficulties confronting the field geologist in Vitilevu, which can be appreciated by anyone who has visited the island, make the successful accomplishment of this systematic study a notable achievement.

R. T. C.

Um das geologische Weltbild. By ERICH HAARMANN, Berlin. Stuttgart: Ferdinand Enke, 1935. Pp. xi+108; figs. 23; map 1. Rm. 5.80.

CONTENTS

1. Introduction
2. Only a few fundamental concepts of geology are completely established
3. The lack of adequate training in physical thought
   a) The loose application of physical terms and the lack of clearness of physical conceptions
   b) The geologist and physics
4. Are mechanical laws applicable to the earth's crust?
5. Mechanical properties of the crust
   a) The multitude of variables
   b) Anisotropy of the crust
   c) Does the mosaic of the crust consist of rigid and mobile blocks?
   d) The anisotropic crust is in its totality quasi-isotropic
6. The registration and reproduction apparatus "man"
7. Review
8. Preview
9. Footnotes, literature, register, etc.

Haarmann's book is an appeal to all geologists for self-criticism. Without attempting to discuss geologic theories comprehensively in textbook style, the author aims at the weakest points of our conceptions and stimulates thinking. Our geologic ideas change from time to time and are large-

ly influenced by the *Zeitgeist* to which we all are subject. Whatever seemed adequate yesterday may be absurd tomorrow. A concept may be destroyed while being built up, through increasing knowledge. "Be critical against yourself and learn to take criticism from others; co-operate and do not think that you are dealing with facts because you deal with interpretations of masters." Study the evolution of ideas in the history of geology and "you may realize that your followers may laugh about you as they do about the description of a reptile skeleton as being the remainder of a bedeviled human."

Haarmann calls for greater clarity in thinking and more accuracy in the application of the laws of physics in geologic interpretation. Less specialization is needed. An overspecialized geologist is not likely to arrive at a broad conception; he is chiefly a technician.

Whoever uses an instrument, knows its constants and corrections, but few geologists seem to care about their own "constants" and personal factors.

Haarmann also says: "Errors are not gallows, but waymarks." We learn through our mistakes, but only if we recognize them.

The little book is very well written: indirect or involved language is carefully avoided. Good illustrations may help the non-German reader considerably. It seems to the reviewer that this appeal should find many followers.

ERNST CLOOS

On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland, Part III: *The Aland Islands*. By J. J. SEDERHOLM. Bulletin de la Commission Géologique de Finlande No. 107. Helsingfors: Government Press, 1934. Pp. 68; figs. 43; maps 2.

This paper is one of the last works of the late Professor J. J. Sederholm. In it he continues his systematic study of the effects of granite invasion into various types of country rocks, discussing, as in the other papers of this series, not only the migmatites but all the rocks of the area. Emphasis is placed on petrology, the complicated structure being left for future study. Described at length are certain lamprophyric rocks associated with the earliest of the three Archean granites, and the Enklinge series (Bothnian) of sediments and volcanics. While having mainly a granitic composition, these islands show small but important areas of sedimentary and volcanic rocks. All but the latest (post-Archean) rocks are very highly metamorphosed.

ROBERT GROGAN